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Optimal sensor placement for bridge structural health monitoring: Integration of physics-based models with data-driven approaches

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Abstract

Optimization of sensor configurations for cost-efficient structural health monitoring (SHM) plays a pivotal role in ensuring the safety and longevity of critical infrastructures such as bridges while minimizing maintenance expenses. Infrastructure systems may evolve over time, and their monitoring needs may change. Hence, the best sensor configuration must be designed to be scalable and adaptable to future requirements without major overhauls.
The present work explores this optimization problem as an essential step of the development and implementation of a robust digital twinning strategy, by combining the strengths of physics-based models with data-driven insights. Conventional methods for sensor placement typically rely on expert knowledge, oftentimes resulting in suboptimal configurations and excessive installation costs. Conversely, physics-based models provide a rigorous comprehension of the structural behavior and can inform sensor placement procedures by assessing the impact of sensor locations on the monitoring accuracy. However, these models have limitations, such as simplifying assumptions, uncertainties, and computational complexities. To overcome these issues and upgrade the sensor placement process, data-driven approaches can be integrated to extract patterns, correlations, and unforeseen anomalies.
To demonstrate the effectiveness and benefits of this hybrid framework, a case study of an existing bridge instrumented with sensors is presented. First, a simplified physics-based model is developed and calibrated through real-world data obtained from an extensive dynamic identification campaign comprising 108 instrumented degrees of freedom. Then, a reduced number of sensors are selected through a data-driven optimization strategy as best candidates for the deployment of a long-term monitoring system. Finally, the virtual model is employed to simulate varying damage scenarios and validate whether the sensor location experimentally identified as optimal would remain the best even when structural conditions change. The ultimate goal is to foster proactive maintenance strategies by striking a balance between data quality, sensor coverage, and SHM cost.

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1. Introduction

Recent catastrophic collapses such as Genoa Bridge (Italy, 2018) or Pittsburgh's Fern Hollow Bridge (United States, 2022) demonstrated what lack of preventive maintenance can lead to. Inspections are happening, but the findings from them are often not followed through. This is a critical aspect that cannot be neglected as most of worldwide existing bridges has overpassed its service life. According to the American Society of Civil Engineers, in the United States 42% of the bridges are currently at least 50 years old and about 7.5% are in poor conditions (ASCE, 2021). A similar alarming scenario is witnessed in many other countries, including Italy where a large portion of existing bridges was built after the Second World War.

Traditional approaches for assessing the structural safety of existing bridge infrastructures do require substantial economic and human resources, thus resulting not sustainable in the long run. Hence, efforts are now focusing on smart management policies relying on large-scale approaches and vibration-based structural health monitoring strategies aimed at identifying and ranking maintenance priorities (Zizi et al. 2023). In this context, the implementation of the digital twin paradigm can be crucial. A digital twin is the virtual representation of a physical object, enriched with significant information about its tangible counterpart and capable of evolving together with it. To be a true up-to-date virtual duplicate of the experimental structure, the digital twin should guarantee a continuous exchange of information between physical and virtual realities aimed at tuning the model parameters till the mismatch between numerical and experimental observations is minimized. This dynamic feeding process can be achieved through dedicated monitoring sensor networks installed across the structure for the acquisition of vibration signatures (typically accelerations) and the extrapolation of synthetic features that allow to timely detect deviations from the expected behaviour. Generally, the higher the spatial density of the network, the greater the monitoring fidelity and the accuracy of the physics-based model, but this comes at the expense of time-consuming and costly installations and can yield problems of data overflows (Masciotta et al. 2019), turning the model updating procedure complex and computationally expensive. These issues are further emphasized in case of sophisticated numerical models and, when handling thousands of bridges, they can generate significant difficulties for asset managers and dealers. For these reasons, the implementation of optimal sensor placement (OSP) techniques becomes fundamental to ensure a trade-off between number of deployed sensors, quality of the produced information and sophistication of the model, fostering a more sustainable, widespread, and cost-efficient digital twinning of the road network in the long run. It is also worth stressing that the use of simple, yet reliable physics-based models regularly updated with experimental monitoring data are particularly necessary within a preventive maintenance perspective. Indeed, by simulating different scenarios corresponding to realistic and relevant cases for the structure under investigation, it is possible to forecast the response of the structure and assess whether it is fit for its purposes, ensuring a sufficient performance, or it needs maintenance, providing a timely plan and prioritization of the interventions and activities. At the same time, these simulations allow to evaluate whether the monitoring needs may change over time, ensuring beforehand - without major overhauls – the definition of a streamlined sensor configuration optimized over varying structural conditions and contributing to the wise allocation of public resources.

The present work arises within the context outlined above and aims at proposing a hybrid sensor optimization approach combining the strengths of physics-based models with data-driven insights, being the goal to demonstrate how simple yet informative digital twins can effectively act as supporting tools to assess the impact of sensor locations on the monitoring accuracy and assist decision makers in the context of preventive maintenance of bridge infrastructures.

2. General framework

One of the main issues in the definition of reduced SHM network topologies for cost-efficient monitoring of bridge infrastructures is to guarantee that anomalous changes in the structural response do not remain undetected. This is a common risk in the current monitoring practice, as the design of SHM systems is typically tailored to the current condition of the structure (*ex-ante*) and might not remain optimal if structural changes occur. On the other side, an essential aspect of the digital twinning paradigm is to ensure that the digital counterpart is capable of following the evolution of the physical system, especially in the presence of damage, warning the asset manager as soon as the structural behaviour becomes unacceptable. By simulating likely damage scenarios and predicting the structural response in different conditions, the digital twin can be actually used to tackle the aforementioned limitation and to identify a reduced sensor layout optimized over many structural conditions (*ex-post*), thus able to catch any relevant deviation from the baseline behaviour. However, given the numerous sources of uncertainty typically associated with numerical approaches, the integration of extensive experimental data is pivotal in the calibration phase of the virtual model as well as in the definition of the candidate best sensor configuration(s) for the initial scenario. In particular, vibration-based monitoring data such as accelerations are a well-established source of information on the global structural behaviour and represent the distinctive signatures through which the health conditions of the system can be followed through. On the one hand, the availability of an extensive ambient vibration campaign comprising a large number of instrumented degrees of freedom provides a very high level of knowledge of the structure, allowing to optimize the location of a few relevant sensors starting from real monitoring data. This data-driven approach to OSP constitutes a rather innovative solution, as well-known optimization strategies only rely on numerical models. Data-driven OSP allows to overcome possible issues caused by the limitations and uncertainties present in fully numerical approaches and to include in the optimization problem information regarding real fieldwork constraints that the model would hardly reproduce, such as the effective signal-to-noise ratio among others. On the other hand, the calibration to the current condition of the physical system provided by the experimental data enhances the capability of the model to predict unknown scenarios. Therefore, once the contribution of each candidate sensor to the mode identifiability of the system is evaluated through a data-driven approach, the tuned virtual model can be exploited to assess and validate the identified sub-optimal solutions accounting for different structural conditions.

In light of the above, the objective of the present work is to demonstrate how OSP strategies can be framed within a robust digital twinning paradigm. The main contribution of the OSP, within this framework, is to identify the sensor configuration able to retain the most important modal information about the investigated structure and support the continuous updating process of simple informative digital twins in a reliable, sustainable and cost-efficient way. To achieve this objective, a well-known bridge is used as a case study. From a practical point of view, the *modus operandi* outlined below has been followed for the generation of the digital twin of the investigated structure.

- Phase 1 – Collection of experimental data: Field data coming from geometrical/material surveys and extensive dynamic testing campaigns are collected in order to characterize the structure under investigation. The larger the amount of experimental data, the lower the uncertainties of the system.
- Phase 2 – Generation and calibration of the digital twin: For the specific application at hand, the envisaged digital twin is composed of a numerical finite element model used to assess and predict the structural behaviour in the current condition and in future potential scenarios. This model is conceived to be integrated with data-driven models for damage detection, namely models that process and interpret the data produced by the long-term monitoring system installed in the structure to ensure an early warning upon condition changes. Additional models to document the building or numerically simulate its performance under other non-structural criteria (e.g. sustainability, functionality, etc.) can be included in a federated digital twin without hindering the generality of the framework here discussed.
- Phase 3 – Data-driven OSP: The best location for a pre-defined number of sensors is selected by reducing the candidates from the many more degrees of freedom instrumented in the preliminary monitoring or dynamic identification, allowing to consider real fieldwork signals and their actual strength in the optimization process. The reduced number of sensors are expected to retain a high information quality and extent, ensuring a straightforward interpretation of the actual structural condition, preventing the generation of an unmanageable quantity of data and containing the costs to purchase, install and maintain the monitoring network.
- Phase 4 – OSP model-based validation for damage identification: The capability of the monitoring system to early detect anomalous variations in the recorded data, likely due to damage onset or evolution, is tested by simulating the structural response in different expected damage scenarios. The goal of this phase is to verify that the features extracted from the monitored signals at the reduced sensor locations significantly change in damaged conditions when compared to the undamaged baseline, ensuring the implementation of a reliable automated damage-identification strategy based on the continuous analysis of the vibration monitoring data.

3. Collection of experimental data

The benchmark case-study structure used in the present work is the Z24 bridge, an overpass of the Bern-Zurich highway built in Switzerland in 1963 as a part of the road connection between the villages of Koppigen and Utzenstorf. It was a classical post-tensioned concrete bridge with a continuous girder layout featuring a mid-span of 30 m, two side spans of 14 m and two sliding slabs of 2.7 m at the approaches (Figure 1). The deck was supported by two intermediate piers clamped into the girders, while the abutments consisted of a triplet of pinned columns connected to the girders through hinges. All supports were rotated with respect to the longitudinal axis of the deck, resulting into a skew bridge. The structure was originally built as a freestanding frame; the approaches and the abutments were backfilled later. Because a new railway adjacent to the highway required the construction of a new bridge with a larger side span, at the end of 1998 the Z24 was demolished.

Before complete demolition, short-term progressive damage tests took place in the framework of the European research project SIMCES – System Identification to Monitor Civil Engineering Structures (Peeters and De Roeck, 2001), whose main aim was to deliver a proof of feasibility for vibration-based structural health monitoring of civil engineering structures. Therefore, before and after each damage scenario, the bridge was subjected to forced and ambient vibration tests to evaluate the variation of its dynamic features. A very dense measurement grid was defined in order to acquire the acceleration response of 291 degrees of freedom distributed both on top of the bridge deck (3 parallel lines of 45 measurement points) and on the pillars (2 parallel lines of 8 measurement points), see Figure 1. Per each test, signals were sampled at 100 Hz for approximately 11 minutes, delivering a total of 65536 datapoints per channel. Table 1 summarizes the dynamic identification results for three significant scenarios experimentally measured: 1) undamaged Reference Scenario (RS), 2) settlement of the pier foundation at 44 m (DS_1), and 3) failure of the concrete hinges at the abutments (DS_2). The identified experimental modes are shown in Figure 2. An exhaustive description of the entire monitoring campaign falls outside the scope of the present work and the reader is referred to (Peeters and De Roeck, 2001) for details.

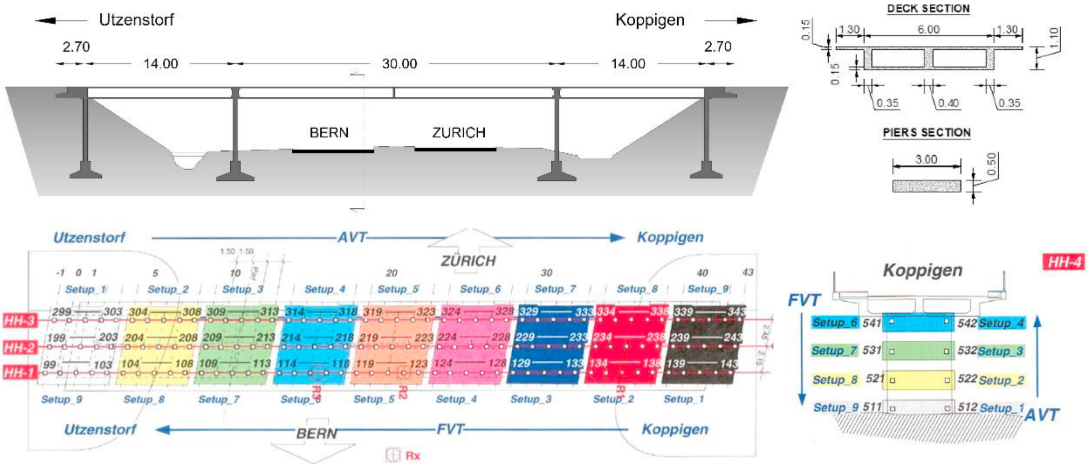


Figure 1. Geometric features of the Z24 bridge and overview of the experimental sensor layout.

Table 1. Evolution of the Z24 modal features under different structural scenarios.

Mode	RS	DS_1			DS_2		
	$f_{i,\,exp}$ [Hz]	$f_{i,\,exp}$ [Hz]	Δf [%]	$MAC_{RS\text{-}DS1}$	$f_{i,\,exp}$ [Hz]	Δf [%]	$MAC_{RS\text{-}DS2}$
1	3.88	3.69	−4.90	1.00	3.85	−0.77	1.00
2	5.02	4.92	−1.99	0.96	4.69	−6.57	0.97
3	9.86	9.27	−5.98	0.75	9.75	−1.12	0.53
4	10.28	9.66	−6.03	0.82	10.18	−0.97	0.81
5	12.69	12.19	−3.94	0.70	11.71	−7.72	0.61

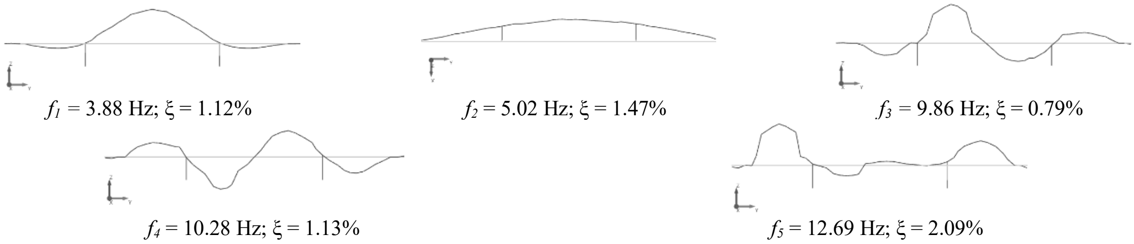


Figure 2. Experimental vibration modes of the Z24 bridge (frequencies and damping ratios refer to the undamaged scenario).

4. Generation and calibration of the digital twin

To generate the core of the digital twin, the Z24 bridge was numerically simulated using NOSA-ITACA code (Girardi et al. 2023), a non-commercial FE software developed in house by ISTI-CNR for the analyses and calibration of linear elastic and/or masonry structures (www.nosaitaca.it/software/). The scope was to take advantage of the dense sensor network experimentally available to build a simple yet finely calibrated physics-informed digital twin without resorting to sophisticated and time-consuming modelling strategies. To this end, the channels belonging to the central sensor array deployed on top of the bridge deck were assumed as experimental reference DOFs, counting a total of 108 measured channels: 18 in transversal, longitudinal and vertical directions, and 27 in transversal and vertical directions. Accordingly, the numerical model consisted of 176 Timoshenko beam elements of 0.5 m length each (element n. 9 of the library), 177 nodes and 1062 degrees of freedom. Aiming at replicating the real geometry of the structure, the beam elements of the deck were assigned with a two-cell box-girder cross section while those of the piers with a solid rectangular cross section.

A homogeneous material with Young's modulus E = 25.0 GPa, Poisson's ratio v = 0.2 and mass density ρ = 2500 kg/m^3 was adopted in the first phase. Afterwards, a finite element model updating was performed by varying the elastic modulus and the boundary conditions at the free ends of columns, piers, and deck of the bridge model till the difference between experimental and numerical modal features of the reference undamaged scenario was minimized. As a result of the calibration process, a Young's modulus E = 37.5 GPa was obtained, while the hypothesis of hinges as boundary conditions resulted to be the optimal solution in terms of frequencies and mode shapes matching. Table 2 summarizes the modal results obtained downstream the calibration process in terms of frequencies, relative percentage error and MAC values between corresponding modes. The spatial configuration of the numerical (predicted) vibration modes is shown in Figure 3; as it is possible to see, the first mode is a symmetric bending mode featuring a vertical deflection of the main span in the XY plane, the second mode involves a transversal bending of the bridge deck in the XZ plane, the third mode is an asymmetric bending mode with a double-curvature vertical deflection of the main span and the fourth is a symmetric vertical bending mode with greater deflections at the side spans. It is noted that, despite the use of a beam-like model which makes it unfeasible to catch the torsional motions of the deck, four of the main vibration modes of the bridge are well identified.

Table 2. Comparison between experimental and numerical modal results of the bridge in the reference undamaged scenario.

Mode	$f_{i,\,exp}$ [Hz]	$f_{i,\,num}$ [Hz]	$\lvert\Delta f\rvert$ [%]	MAC
1	3.89	3.87	0.51	1.00
2	5.02	5.02	0.00	0.99
3	9.86	9.86	0.00	0.85
4	12.69	11.88	6.38	0.78

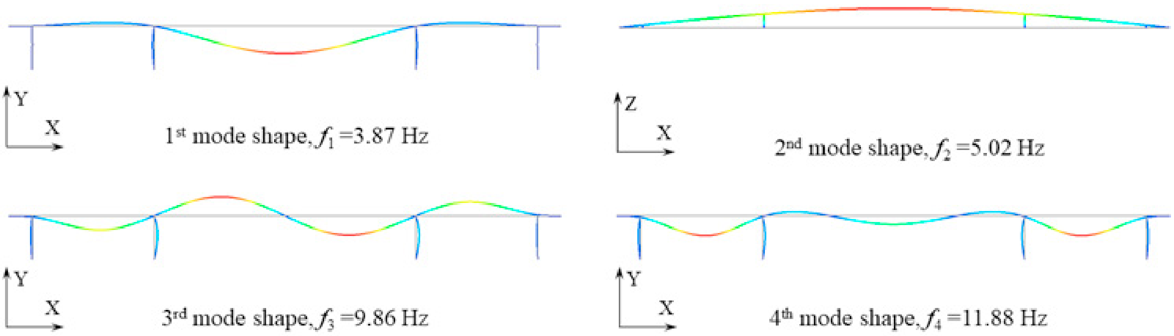
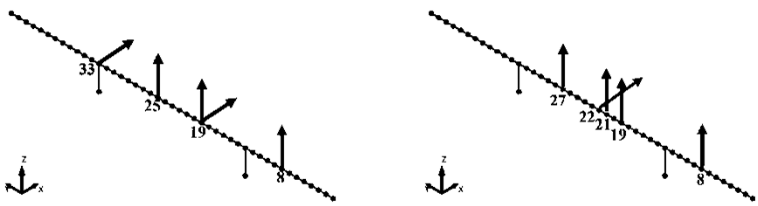


Figure 3. First four numerical mode shapes of the Z24 bridge after the calibration process.

5. Data-driven optimal sensor placement

Making use of the same amount of benchmark experimental data from the Z24 bridge, Masciotta et al. (2023) demonstrated that by applying a modal-based multi-objective optimization it is possible to assess the performance of different OSP algorithms and identify, out of many sub-optimal candidate solutions, a sensor configuration optimized over different structural scenarios, thus ensuring a cost-efficient monitoring of the infrastructure in the long run. Following a fully data-driven OSP approach, six known heuristic algorithms were tested: (i) Effective Independence (EfI) (Kammer, 1991); (ii) Eigenvector Component Product (ECP) (Larson et al. 1994); (iii) Mode Shape Summation Plot (MSSP) (DeClerck and Avitabile, 1996); (iv) Average Drive Point Residue (ADPR) (Chung and Moore, 1993); (v) Weighted Average Drive Point Residue (WDPR) (Chung and Moore, 1993); (vi) QR Decomposition (QRD) (Schedlinski and Link, 1996). After reducing the dimensionality of the problem from 108 to 5 DOFs, namely to the least acceptable number of degrees of freedom to ensure the identification of the main experimental vibration modes of the bridge, each algorithm allowed evaluating the contribution of each candidate sensor to the mode identifiability of the system and obtaining a candidate sensor configuration according to a specific metric. It is interesting to note that many measurement points were commonly identified as best by all the six heuristics. Details concerning the algorithm formulations and the performance evaluation process can be found in Masciotta et al. (2023) and are not repeated in the present work. For the purpose of this study, only the two data-driven sensor configurations enabling to retain the highest and most accurate amount of modal information about the bridge over different experimental scenarios are considered: the configuration obtained from the Effective Independence (EfI) method, hereafter referred as OSP 1, and the configuration resulting from the QR Decomposition (QRD) method, henceforth referred as OSP 2 (Figure 4).



OSP 1 (EfI)
Ch: 19x-19z-8z-25z-33x

OSP 2 (QRD)
Ch: 19z-27z-22x-8z-21z

Figure 4. Optimal sensor configurations for the Z24 bridge estimated through a fully data-driven approach.

6. OSP model-based validation for damage identification

In order to explore the problem of sensor optimization by integrating data-driven insights with physics-based information and to validate whether the sensor layouts estimated through the data-driven OSP approach could remain optimal in the presence of new structural changes, the digital twin described in Section 4 was exploited to simulate potential damage scenarios different than those experimentally measured and considered in the optimization problem addressed in Masciotta et al. (2023). The first damage scenario (DS_1) involved a local stiffness reduction of the bridge girder in the main span, 3 meters away from the Utzenstorf pier, whereas the second damage scenario (DS_2) involved a stiffness reduction of the bridge girder in the middle of the side span (Koppigen side), besides the damage of the main span (Figure 5). The decrement in stiffness was simulated by applying an increasing penalty factor to the Young's modulus of the beam elements belonging to the selected damage areas. Table 3 reports the evolution of the eigenfrequencies of the bridge for the simulated scenarios along with the variation of MAC values between corresponding modes. It is noted that frequency parameters appear very sensitive to local stiffness variations as the extent and intensity of damage increase: in fact, given the static scheme of the bridge, these changes affect the dynamic response of the structure at a global level. Conversely, modal deflections show almost no sensitivity to the simulated damage except for the fourth mode in DS_2 which is indeed characterized by a higher number of inflection points, thus greater modal shifts in the presence of local damage phenomena.

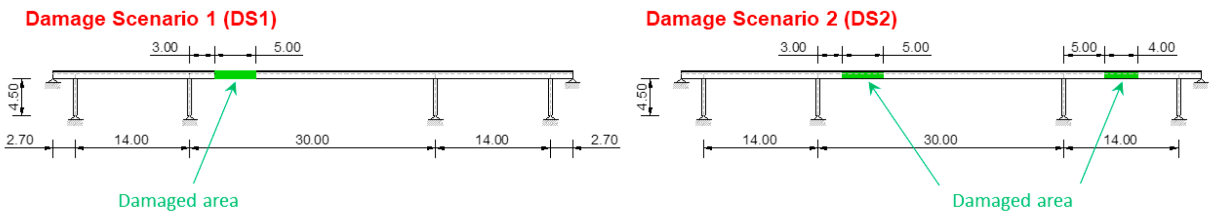


Figure 5. Numerical damage scenarios: position and extent of the damage areas along the bridge deck.

Table 3. Variation of the modal results of the bridge under the simulated damage scenarios.

Mode	$f_{i,RS}$ [Hz]	$f_{i,DS1}$ [Hz]	Δf [%]	MAC_{RS-DS1}	$f_{i,DS2}$ [Hz]	Δf [%]	MAC_{RS-DS2}
1	3.87	3.85	−0.67	0.99	3.78	−2.49	0.99
2	5.02	4.95	−1.40	0.99	4.77	−5.00	0.99
3	9.87	9.51	−3.67	0.98	8.84	−10.39	0.98
4	11.88	11.81	−0.60	0.99	10.90	−28.24	0.85

To evaluate the goodness of the OSP solutions estimated through a fully data-driven approach, the modal features extraction process is repeated by scaling the numerical DOFs of the model down to the five DOFs considered in each reduced sensor configuration. The results obtained for the different structural conditions (RS, DS_1 and DS_2) are presented in Table 4 and Table 5. It is found that both configurations (OSP1 and OSP2) succeed in retaining the main modal information of the bridge, leading to the accurate identification of all the main vibration modes. Deviations from the baseline behaviour are caught by each layout both in terms of frequencies and modal deflections, reading indeed modal shifts for the sole fourth mode (MAC < 0.88), i.e. the mode identified as the most sensitive to damage in the full sensor layout. Still, looking at the off-diagonal terms of the AutoMAC matrix estimated for each scenario and for each sensor configuration, it can be deduced that the placement that better ensures the identification of orthogonal and linearly independent modal vectors corresponds to OSP2. This result corroborates the outcome of the data-driven sensor optimization, demonstrating that the configuration identified as the best for specific known scenarios is also the best in case of other simulated structural faults and can be effectively selected to support the continuous updating of the digital twin.

Table 4. Variation of frequencies and MAC values of the bridge modes estimated from the reduced sensor configurations over different scenarios.

Mode	OSP1|OSP2			OSP1		OSP2	
	$f_{i, RS}$ [Hz]	$f_{i, DS1}$ [Hz]	$f_{i, DS2}$ [Hz]	MAC_{RS-DS1}	MAC_{RS-DS2}	MAC_{RS-DS1}	MAC_{RS-DS2}
1	3.87	3.85	3.78	1.00	0.99	0.99	0.99
2	5.02	4.95	4.77	0.99	0.99	1.00	1.00
3	9.87	9.51	8.84	0.99	0.98	0.99	0.99
4	11.88	11.81	10.90	0.99	0.88	0.99	0.83

Table 5. Average of the off-diagonal terms of the AutoMAC matrices estimated for each scenario using data from the full numerical sensor configuration (NSP) and from the reduced data-driven optimal sensor configurations (OSP).

	NSP	OSP1	OSP2
RS	0.001	0.049	0.027
DS_1	0.001	0.047	0.024
DS_2	0.005	0.027	0.017
Avg	0.002	0.041	0.023

7. Conclusions

This work demonstrated how hybrid sensor optimization approaches combining the strengths of physics-based models with data-driven insights can be exploited as valuable means for a sustainable and cost-efficient digital twinning of bridge infrastructures in the context of long-term SHM. To this end, the monitoring data from an existing bridge were first employed to derive an optimal sensor configuration based on known experimental scenarios and then to calibrate a simple informative digital twin of the structure aimed at validating the data-driven OSP over new simulated structural conditions. It was highlighted that measured vibration signatures are essential to address the sensor optimization problem, yet physics-based models refined through real-world data are crucial to predict unknown scenarios and assess the impact of sensor locations on the monitoring accuracy under evolving structural conditions.

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