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Procedia Structural Integrity 62 (2024) 924–931

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

On the use of MTInSAR data and UAV photogrammetry to monitor the behavior of existing bridge portfolios

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Abstract

Bridges play a vital role in road networks, and ensuring their safety and preservation is of utmost importance to both management companies and the scientific community. On the other hand, ensuring a continuous assessment of the bridge portfolios health state requires high costs (e.g., sensor-based monitoring), which leads to employ different techniques to identify the most critical cases and implementing risk mitigation measures. With this goal in mind, this paper presents the application of two of the most actual and attractive cost-effective techniques for purpose of existing bridge portfolios health state monitoring: (a) multitemporal interferometry via synthetic aperture radar (MTInSAR) data; (b) unmanned aerial vehicle (UAV) photogrammetry. In detail, the paper deals with the use of the two above methodologies, where MTInSAR data can be employed to perform a qualitative assessment of the spatial displacements and velocities characterizing the focused bridges, while UAV flight surveys can be used to identify the occurrence of displacement phenomena (e.g., landslides) in the area immediately close around the observed structures. After describing pros and cons of the two approaches, an application is provided on an existing bridge, for which MTInSAR temporal series are analyzed over 1 year of observation, while UAV surveys are performed at the start and at the end of the considered period. From the combination and the comparison of the techniques, some insights are provided, opening new scenarios in the field of the structural health monitoring of existing bridges portfolio.

Keywords: MTInSAR Data, Unmanned Aerial Vehicle, Existing Bridge Portfolios, Structural Health Monitoring.

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10.1016/j.prostr.2024.09.124

Nomenclature

α	azimuth angle
φ	phase
μ	mean
θ	incidence angle
σ	standard deviation
A	amplitude
ASC	ascending
CSK	COSMO-SkyMed
DEM	digital elevation models
d_{LoS}	average displacement along the line of sight
DSC	descending
GNSS	global navigation satellite system
GPS	global positioning system
MTInSAR	multitemporal differential interferometry via synthetic aperture radar
LoS	line of sight
PSs	persistence scatters
RC	reinforced concrete
SEN	Sentinel-1
V_{LoS}	average velocity along the line of sight
UAV	unmanned aerial vehicle

1. Introduction

The recent events about the collapse of significant bridges in Italy have prompted public authorities to propose new strategies for ensuring the safety of the existing bridge portfolios, aimed at establishing new and robust risk mitigation plans. In this context, road management companies are directly involved, which are called to evaluate the condition of the existing bridges and to implement appropriate strategies to prevent future fatalities. To rule the practice of assessment of the existing bridges, one of the key measures adopted by the Italian government was the release of the new guidelines for the structural safety of existing bridges (MIT, 2021), which are becoming mandatory for the management companies. The new guidelines advocate a systematic multi-level approach to employ on the entire national bridge portfolio, with the main aim to identify the bridges presenting the most critical conditions and, for those, to apply adequate monitoring and maintenance strategies, including the possibility of demolition and reconstruction. The proposed approach is developed for carrying out six consecutive levels of analysis with increasing complexity. The first three levels consist in a preliminary screening to identify the most critical cases, which will be object of further in-depth actions, varying from the retrofit to the service limitations, as by employing a traffic reduction or weight restrictions for trucks.

In the initial phase of the application of the new Italian guidelines, management companies in collaboration with the scientific community focused on the development of the prescriptions related at the first three levels, named levels 0, 1, and 2. Looking in detail these latter, Level 0 consists in the collection of original documentation for each bridge in the focused road network. Original design, drawings, retrofit and maintenance plan are some papers among the documentation to retrieve, even though data collection is oriented on the analysis of all risks characterizing bridges, which implies the gathering of structural, seismic, hydraulic, geotechnical, and geological information. Moving to level 1, this consists in performing periodic inspections of each bridge within the road network. Well-trained surveyors are involved to meticulously examine the main defects affecting all structural elements of the observed bridges (e.g., decks, beams, piers, supports, abutments), with the main aim of identifying potential vulnerabilities and issues arising from environmental risks. Based on these inspections, level 2 comes into play, wherein a risk classification can be performed. The quantification of the overall risk (defined through a risk class) is derived from the quantification of sub-risk classes associated to all considered hazards, depending on structural, seismic, hydraulic, and geological factors. About the risk classes, the guidelines define five different levels: low, medium-low, medium, medium-high, and high. Depending on the risk level, management companies can decide the appropriate actions to involve for each structure. For instance, bridges classified as high-risk undergo level 4 assessments, for which it is necessary to assess different limit states (e.g., serviceability, operability), and for which a dynamic structural monitoring is recommended. Instead, in the case of low-risk, bridges should be re-evaluated after a fixed time by performing on-situ surveys as prescribed by the level 1 (e.g., checking the health state of the bridge with a time intervals of six months between consecutive inspections).

It is worth noting that in the proposed system, some problems can be highlighted. First, in level 0, documentation is often unavailable for older bridges, such as reports about hydraulic and geological aspects characterizing the original design of the bridge. Still, when coming to level 1, it is worth considering that only few well-trained surveyors are available, which should inspect hundreds of bridges within a short timeframe, leading to high inspection cost. In addition, aspects like lapses in attention, subjectivity, difficulty in accessing some parts of the bridge (e.g., supports) complete the complex frame of the on-site inspections world. In the end, a main problem observed during the application of the guidelines prescriptions is due to the identification and the definition of slow kinematic phenomena (e.g., subsidence, landslides), which only just a truly expert eye can highlight after an overall inspection of the area around the structure. In light of these problems, it is evident that a support to the inspection operations is necessary, especially for those phenomena characterizing the surrounding environment of the bridge. With this regard, the paper presents an ongoing study aiming to explore the use and the combination of two new technologies, that is, multitemporal interferometry via synthetic aperture radar (MTInSAR) data and unmanned aerial vehicle (UAV) photogrammetry, for purpose of existing bridge portfolios health state monitoring. Both techniques are two of the most attractive cost-effective methodologies, where through MTInSAR data it is possible to perform a qualitative assessment of the spatial displacements and velocities characterizing the focused bridges, while through UAV flight surveys it is possible to observe some displacement phenomena (e.g., landslides), especially comparing flights performed in two different times. The paper reports some elaborations and activities experienced by the authors in the latest two years and it aims at highlighting pros and cons of both methodologies, attempting to combine information provided by the two techniques for easing the identification of the interaction between the bridge and the surrounding area.

2. Use of MTInSAR and UAV in the monitoring of existing RC bridges: state-of-the-art

In the recent years, several new cost-effective techniques were strongly developed, finding their application in the field of existing bridge monitoring. Among these, MTInSAR data and UAV photogrammetry represent useful tools, which can be improved for simplifying the phase of on-site survey of existing bridges.

Talking about MTInSAR data, SAR sensors area defined as active sensors that use a transmitter antenna to illuminate the ground scene along the Line-of-Sight (LoS). Each emitted electromagnetic wave is partly absorbed and partly reflected to the transmitter antenna. The key feature of SAR sensors is that during the flight the antenna can synthesize an array of antennas for achieving greater spatial resolution in the azimuth direction. This latter, almost aligned with the North-South direction, is represented by the azimuth angle (α). Another relevant parameter is the incidence angle (θ), which measures the angle between the vertical direction and the LoS direction to the focused point. Thus, at the passage of each satellite, a SAR image is acquired according to two acquisition geometries, that is, ascending (ASC) and descending (DSC). From the SAR image, a matrix can be defined, characterized by an amplitude (A) and a phase (φ). The first one allows to identify Persistent Scatterers (PSs), points corresponding to buildings or structures; the second one is used to evaluate LoS displacement time-series for the PS, through the definition of the differences of φ among master image and the other ones in the imagery. MTInSAR algorithms can track displacements with a millimeter-accuracy monitoring for satellite imagery acquired with X-band sensors, as indicated in REA-CNR et al. (2020) and allow to extract some useful information, such as Latitude, Longitude, Height above sea level, LoS displacement time series (d_{Los}), average LoS velocity (V_{LoS}), and coherence. Spatial and temporal resolution should be also evaluated, where the first one depends on the radar wavelength (e.g., COSMO-SkyMed, CSK, satellites present X-band sensors with wavelength of 3.1 cm, while Sentinel-1, SEN, satellites present C-band sensors with wavelength of 5.6 cm), while the second one differs among constellation (e.g., CSK presents a revisit time between 4 and 16 days, while SEN presents a revisit time of 12 days). Additional details on SAR data and constellations can be found in Calò et al. (2023). Numerous studies in the scientific literature have explored the application of MTInSAR measurements to assess various aspects of bridge behavior. Nettis et al. (2022) introduced a geoprocessing pipeline to interpret deformation scenarios on bridges within a road network. Authors performed a monitoring of an area characterized by subsidence with the aim to assess the bridges at risk and prioritize further monitoring. Farneti et al. (2022) developed a framework for assessing the displacements of multi-span bridges using MTInSAR, on the case of Albiano-Magra Bridge in Italy. In a similar vein, Macchiarulo et al. (2022) identified significant displacements in the surrounding area of the Himera viaduct, which partially collapsed in 2015. Several studies, including those by Milillo et al. (2019), Milillo et al. (2020), and Lanari et al. (2020), investigated the collapse of the Polcevera Viaduct in Genova, Italy, utilizing MTInSAR algorithms to identify potential collapse precursors.

Moving to the use of UAV for purpose of bridge monitoring, the main advantage provided by this technology is the possibility to retrieve high or very high-resolution images from inspection surveys. Several outputs can be obtained from these images, through specific processing. Firstly, it is worth mentioning three-dimensional point clouds, which is characterized by georeferenced points that materialize points of infrastructures in the space. Another product is a digital elevation models (DEM), which is a computer graphics representation of elevation data to represent terrain or overlaying objects, containing both positional and elevation information. Still, from UAV flights output, orthomosaics can be derived, which are raster images composed of colored pixels resulting from the orthorectification of images within the photogrammetric dataset, meshes representing continuous surfaces derived from three-dimensional space points that become the vertices of triangles, and textures created by stitching images from the photogrammetric dataset to overlay the model. UAV photogrammetry found extensive use in monitoring landslides. Although it may not provide highly accurate or real-time information, the main advantage is the possibility to cover larger landslide areas. For instance, Devoto et al. (2020) emphasized the benefits of employing UAV-based digital photogrammetry in the study of slow-moving coastal landslides along the northwestern coast of Malta. UAV-generated products like 3D models and orthomosaics were used to identify and categorize coastal megaclast deposits. Coming to the use of UAV on bridges, very few studies exist in the literature, mainly oriented to two objectives: (a) to monitor landslides in the surrounding area of a bridge; (b) to acquire data for improving on-site inspections. Regarding the first topic, Ozcan and Özcan (2021) conducted a study about a multi-temporal monitoring of the area of Turkish Bogacay lagoon plain, which included a bridge located near a flood-prone river. Authors performed a high-resolution topographic survey, acquired over two consecutive years, through UAV in order to identify morphological changes in the river channel. After extracting DEMs, repeated UAV survey data were compared to estimate deposition and erosion volumes. Concerning the second topic, Gaspari et al. (2022) provided a new methodology for bridge inspection, concerning in the combination of traditional topographic through GNSS technique and photogrammetry using UAV-mounted cameras. Still, authors explored the possibility to combine the UAV with the LiDAR technology. Still, Wang et al. (2023) proposed a framework for rapid seismic risk assessment of bridges, in which an estimate of the capacity/demand ratios and the related uncertainties was provided, only by using the limited information obtained from UAV aerial photogrammetry. Concerning the combination of UAV photogrammetry and SAR data, Meng et al. (2020) investigated at large-scale the evolution of a landslide in northwestern China. UAV data were used to identify sudden landslides, enabling the analysis of erosion (decreased elevation) and accumulation (increased elevation) zones based on differences in elevation models obtained from surveys. Finally, there are numerous studies in the literature that evaluate the feasibility of UAV aerial inspection for quantifying bridge damages. For instance, Duque et al. (2018) developed a four-phase damage quantification protocol for bridges, involving image quality assessment and image-based damage quantification.

3. On the combination of UAV photogrammetry and MTInSAR data: a case study

The proposed approach in this paper consists in performing surveys of bridge by combining the two technologies above discussed. In particular, the aim of the method consists of supporting the displacement time-series from MTInSAR elaboration with UAV flights periodically carried out over the surrounding area of the bridge. The idea behind this approach is to exploit the advantages related to each technique. In particular, elaborating MTInSAR data and time series for the available PSs can provide displacements in an established period of observation for the structure, and this can provide some information on the movements that the bridge is suffering over the considered period. Instead, UAV surveys, performed at the extremes of the selected period of observation, can provide an overview on the movements of the surrounding area around the bridge, which could be qualitatively related to the observed displacement on the structure. Obviously, the approach is merely qualitative, considering that the two measurement campaigns and the two technologies cannot be directly correlated, given that the techniques present different tolerances in the measures and provide different output. Nevertheless, the data fusion could add more value at the inspections, especially when the main risk characterizing the bridge is related to slow kinematic phenomena (e.g., landslides, subsidence).

Following this approach, a real-life case study (for which no detailed information can be provided for privacy reasons) was investigated and surveyed with both techniques. It is worth noting that the bridge is located in an area characterized by diffuse landslides phenomena, and with this investigation, it is possible to estimate if the above phenomena affect the structural behavior. The case study is a multi-span simply supported prestressed RC girder bridge, built in the 1950, and constituted by seven spans supported by piers and seat-type abutments. Each span is characterized by four prestressed RC beams, transversely connected by RC cast-in-place diaphragms and by an RC slab with thickness of 0.2 m. The bridge superstructure is connected to piers and abutments through elastomeric bearings. The length of the spans ranges from 32 m and 33 m. For the case at hand, a period of observation going from 2021 October to 2023 July was selected, for which satellite data were available. UAV flights were performed on the abovementioned dates. The surrounding area around the bridge was selected without an established criterion, but only by considering the capability of the used UAV to does not lose the signal. Regarding MTInSAR data, only DSC imagery was collected by SEN constellation, for which detailed features are reported in Table 1, with an output of 42 PSs on the selected area. As expected, all the PSs are located on the bridge surface, also accounting for a geo-positioning error of the scatterers. Once the PSs were selected, the d_{LoS} time series was found by computing the average for each time step, by attributing the time series to the centroid of the bridge and computing mean, μ, and standard deviation, σ, of all PS.

Table 1. Number of labels for each defect for the available dataset.

Satellite	Mode	Spatial resolution	Pass type	Time span	Incidence angle θ [°]	Azimuth angle α [°]
SEN	STRIPMAP	5 m x 5 m	DSC	12 April 2017 21 August 2023	41.218	9.724

Regarding the UAV photogrammetry, the flights were carried out through a mini-UAV of the type DJI, equipped with a 12MP camera, an internal multiconstellation GPS, and an inferior sensor system. Before performing the flights, some markers were selected, established by exploiting the road signs present on the bridge and some points close to the pier, to guarantee the correct geolocation of the further model (also possible through the real time kinematic system enabled with an accuracy of 0.010 m). Fig. 1 shows the used UAV and the phase of markers acquisition. After, an automatic flight was performed according to a regular and continuous sequence of observation points, to scan the entire examined area, and maintaining a fixed camera direction and flight altitude for the entire duration of the acquisition time.

Fig. 1. Type of UAV used for the survey and phase of ground control points acquisition.

After collecting data, the first step was the elaboration of the MTInSAR data. Looking at the obtained results, μ and σ, evaluated through the least square regression method, were equal to -0.14 mm/y and 0.05 mm respectively (despite a low value of the coefficient of determination). From the obtained quantities, the cumulative displacement over the period of observation can be calculated as the product of V_{LoS} times the considered time interval. As result, a downward cumulative displacement of 0.25 mm was found (see Fig. 2). Only by observing this result, it is possible to affirm that the bridge in the period of observation did not suffer important displacements, which means that the well-known landslide phenomena did not affect the behavior of the bridge.

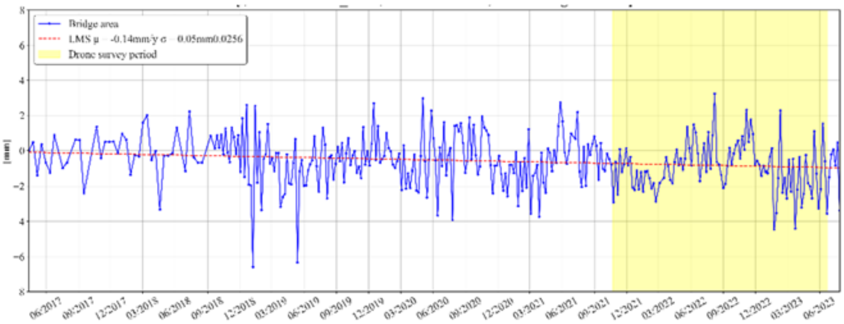

Fig. 2. On blue, PSs average DSC LoS displacement time series obtained with SEN SAR data (2017 May – 2023 July); on red, Least Square Method regression computed over the satellite observation period; on yellow, drone survey period (2021 October – 2023 July).

Using the output of the UAV photogrammetry, different outputs were produced (analogously for both performed flights). First, a point cloud analysis was performed, georeferencing the points in the WGS84 reference system and results shows a dense point cloud referring to the 2021 survey consisting of 85.968.267 points from 268 photos and 5 markers, and a dense point cloud referring to the 2023 survey consisting of 125.123.526 points from 545 photos and 5 markers. This difference may sound abnormal, since the area surveyed in 2021 is evidently larger than that of 2023. However, the higher number of points of the cloud of 2023was due to a lower elevation flight, which required a higher number of frames, in order to guarantee the necessary front and side overlapping for point cloud reconstruction. Therefore, a higher number of points was retrieved by processing the frames of the 2023 flight. After, some DEMs were produced and, from these latter, orthomosaics were derived to have measurable surfaces. Figs. 3 and 4 show all the elaborations made after processing data from UAV surveys, respectively for flight in 2021 and flight in 2023.

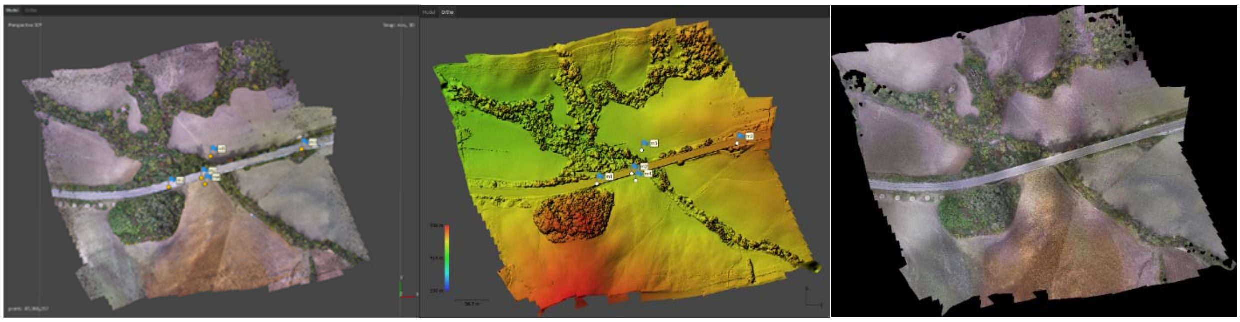

Fig. 3. Cloud points, DEM, and orthomosaic of the investigated area using UAV photogrammetry made in 2021.

In order to assess if some differences occurred in the area around the bridge in the observed period, the DEMs were compared. With this scope, using a geographical information system, both DEM were overlapped, and a section of the Earth surface was observed, transversally cutting the bridge and the surrounding area. In this way, a comparison between the terrain profiles can be carried out, showing the occurrence of altimetric differences attributable to landslides or, in the worst case, to bridge movements. This elaboration is shown in Figs. 5 and 6, where in the first one the superposition of the DEMs is reported, with the terrain section (red line) and the selected ground position points, while in the second one the superposition of the terrain sections computed for the surveys in 2021 and 2023 is shown.

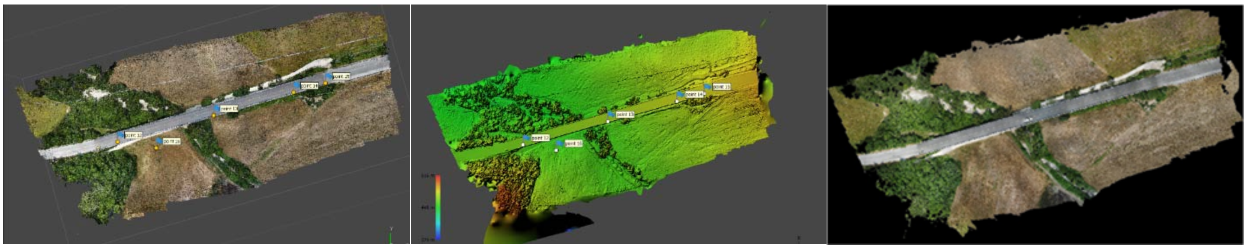

Fig. 4. Cloud points, DEM, and orthomosaic of the investigated area using UAV photogrammetry made in 2023.

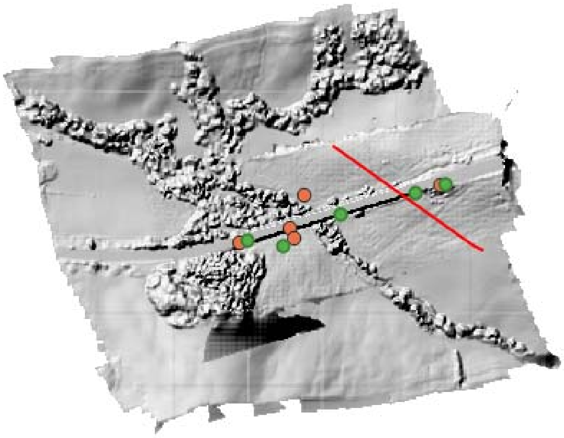

Fig. 5. Superposition of DEMs in 2021 and 2023, line of the terrain section (red line) and markers (green and orange points).

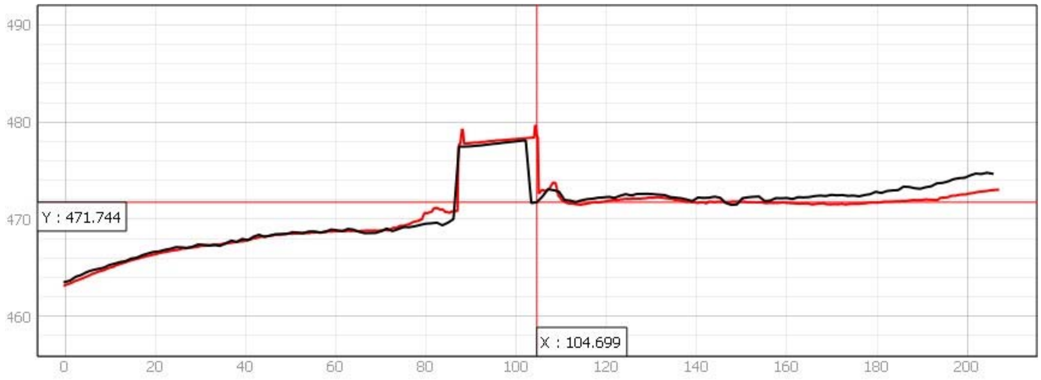

Fig. 6. Comparison of the terrain sections elaborated from the DEMs in 2021 and 2023.

Observing the obtained results, the differences in terms of terrain section are very negligible, considering a certain tolerance proper of the DEMs elaboration, likely related to the different flight altitudes and to the different position of ground control points, due to the impossibility of materializing these point outside the road. Both bridge area and surrounding area do not present substantial variation, evidence that confirms the result obtained from the elaboration of MTInSAR displacement time-series.

4. Conclusions and future developments

The paper presents a study on the use of two cost-effective techniques for the purpose of bridge portfolios monitoring, that is, UAV photogrammetry and MTInSAR data. After describing the characteristics and the potentialities of both techniques, a case study was investigated, for which satellite data and output from UAV flights were elaborated, considering a fixed time of observation. The obtained results showed that, although the methodologies are quite different in terms of accuracy and typology of output, similar outcomes were derived. As a matter of fact, both approaches confirmed that in the period of observation, the surrounding area did not affect the bridge, excluding movements related to landslides phenomena. Although the proposed study is at an early stage and the techniques present some substantial differences and limitations, good potentialities were offered by both methodologies and, above all, by combining the informative contents of the elaborated outputs. Further developments will aim to provide a systematic protocol exploiting UAV photogrammetry and MTInSAR data for monitoring the behavior of existing bridge portfolios.

Acknowledgements

All authors thank the consortium FABRE for the financial support. The fourth author acknowledges funding by Italian Ministry of University and Research, within the project ‘PON-Ricerca e Innovazione 2014–2020, (D.M. 10/08/2021, n. 1062) CUP CODE: D95F21002140006.

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