



Integration, harmonization, and processing of geomatic data for bridge health assessment: the Lastra a Signa case study

Francesco Mugnai¹ · Valentina Bonora¹ · Grazia Tucci¹

Received: 29 November 2022 / Accepted: 20 April 2023 / Published online: 3 May 2023
© The Author(s) 2023

Abstract

A visual inspection, which entails field surveying, such as photodocumentation and footage, is the first step of a multi-level approach to bridge health assessment. Furthermore, the use of surface models, CAD drawings, and orthophotos, guarantees complete and accurate documentation, thus allowing for a better understanding of the environment, the anthropic structures, and their relationships. All the georeferenced surveys' outputs are especially advisable within a perspective of periodical monitoring, as foreseen by national legislation. The work is aimed to study two adjacent bridges over the Arno River in Lastra a Signa, Italy. One of the bridges, Ponte nuovo sull'Arno, is an overpass for motor vehicles. The other one, which is called Passarella sull'Arno, is a pedestrian viaduct. A topographic reference network has been settled using the GNSS survey technique. 3D point clouds of the bridges have been acquired by performing a Laser Scanning survey. A bathymetric survey has been carried out to acquire a 3D point cloud of submerged bridges' parts and the riverbed. Through a Photogrammetric survey from RPAS, an orthophoto of the area has been built. Finally, evidence of historical submerged bridge structures has been identified thanks to the multi beam survey. The work's objective is to integrate surveying geomatics techniques to create a reliable survey of the bridges, the surrounding area, and the riverbed, as support to the most common structural health assessment methods.

Keywords Bridge health monitoring · Bathymetric survey · Point clouds · Integrated survey

Introduction

Civil infrastructure networks in Western Europe and the USA were primarily built in the post-World War II era, most notably in the 1960s and 1970s; some of them could have reached the end of their designed service life (Skokandić et al., 2022). Structural health and strength of structures are influenced by various factors, such as the material production stage, transportation, placement, workmanship, formwork removal, and concrete curing (Mishra et al., 2022). Surveying of infrastructures (Banfi et al., 2022) and surveying data integration (Lo Brutto et al., 2021; Corongiu et al., 2018), are key topics and there is a dense scientific literature that deeply describes several methods (Fan & Saadeghvaziri, 2019; Tang et al., 2020), tools, and approaches (Noardo, 2022) that serve the various purposes of building management (Korumaz et al., 2017; Oreni et al., 2017;

Previtali et al., 2020). Since several recent failures have happened in the last few years, bridges stability assessment is nowadays a crucial subject (Enright & Frangopol, 2000; Rehman et al., 2016; Rizzo & Enshaeian, 2021). In Italy, the “Polcevera” bridge collapsed in 2018 (Bazzucchi et al., 2018), and several cases around the world, report severe safety issues on bridges structures (Corr et al., 2010; Jiménez-Jiménez et al., 2021; Santarsiero et al., 2021). Therefore, improving the management of existing bridges has become urgent to guarantee their safety and preservation, and avoid other disasters. The need for sound, practical and cost-affordable methods is increasingly attracting the attention of researchers (Khedmatgozar Dolati et al., 2021; Li & Ou, 2016; Pucci et al., 2019). Since reliable metric documentation of structures is the basis for any consideration of structural aspects, many examples of geomatics techniques, such as Laser Scanning, GNSS, and Photogrammetry, can be frequently founded in scientific bibliography (Barrile et al., 2019; Riveiro et al., 2013; Valença et al., 2017). In addition to knowing the structure's main dimensions and features, it is necessary to assess any damage that may have occurred due to different types of decay and deformation through periodical or continuous monitoring operations. Many authors show the

✉ Francesco Mugnai
francesco.mugnai@unifi.it

¹ Department of Civil and Environmental Engineering,
University of Florence, Via di Santa Marta, 3,
50139 Firenze, Italy

effectiveness of using radar interferometry, both airborne and ground-based configuration (Gagliardi et al., 2020), to detect structural damages (Kuras et al., 2012; Maizuar et al., 2017) and assess dynamic deformations. More often, RADAR techniques are integrated with sensor networks, even wireless (L. He et al., 2020), mainly composed of MEMS sensors as accelerometers, gyroscopes and strain gauges (Gu et al., 2012; Pieraccini et al., 2019), to carry out long-lasting monitoring. Since systems for making high-resolution point models appeared on the market, various experimental works have tried to compare the performance of Laser Scanning and image-based systems for capturing 3D data of terrestrial, industrial, or heritage objects. Generally, the results were strongly influenced by the operational context: from time to time, one of the solutions has more marked advantages (Baltsavias, 1999). Geomatic techniques can profitably integrate, and sometimes substitute, classical and more common surveying and monitoring approach for Bridge Health Monitoring (BHM) (Bao et al., 2021; Catbas & Avci, 2022; Gaspari et al., 2022; Mugnai F. et al., 2019a; Yu et al., 2016). Performing the assessment and analysis of all existing bridges to evaluate their safety levels and plan the needed measures would require high technical, temporal and financial efforts (Buratti et al., 2021).

Despite the lack of authoritative international legislative guidance, various countries adopted their regulations, often harmonising regional legislation (Wynne et al., 2022).

The Italian Ministry of Infrastructures and Transport (MIT) published the “Guidelines for the classification and the risk management, safety evaluation and monitoring of existing bridges” (Ministry of Infrastructures and Transports, 2020). The document provides indications, approaches, and methods for managing existing bridges. The Italian new regulation focuses on a multi-level approach, as described in the “Italian guidelines for the structural health assessment of bridges” section. In this framework, the state of preservation of bridges (Beltrami et al., 2021; Zambon et al., 2017), which can be inspected directly or through optical cameras, also mounted on remotely piloted aerial systems (RPASs), as well as in situ and remotely performed accelerometric sensors analysis (Sekiya et al., 2016), are crucial tasks to define performance parameters. Both measures and expert opinions are therefore collected using: visual inspections, off-site tests on materials (destructive tests, DT), on-site investigation using the non-destructive tests (NDT), or structural health monitoring (SHM) systems (Dabous & Feroz, 2020; Limongelli et al., 2018), e.g., corrosion in metallic parts such as cables, reinforcements, connections, or girders, that may degrade bridge performance. Integration of different surveying techniques and data (Adamopoulos & Rinaudo, 2021; Alani et al., 2020; Brumana et al., 2014; Fawzy, 2019) is also a crucial approach that often enhances the effectiveness of the structural health assessment procedures (Beshr, 2015; Z. He et al., 2022). A close relationship between technologies and their application context continues to be

illustrated in more recent works, testifying how the improved instrumental performance only partially counterbalances the constraints of each method (Mohammadi et al., 2021). TLS and Photogrammetry allow for documenting out-of-the-water structures sampled in dense point clouds (DPC); resolution and completeness are the main parameters characterising their quality. Submerged structures can be digitised by multibeam mapping systems (MBMS), producing outputs like those obtained for out-of-water structures.

In the literature, various documentation projects propose considering also the contributions offered by thermographic surveys (Alba et al., 2011) to develop BIM models or HBIM, associating semantic content, for instance, related to materials, degradation and conservation interventions (Conti et al., 2020). Others study how to turn BIM into finite elements supporting structural analysis (Barazzetti et al., 2015).

This work aims to describe the integrated application of the various geomatics techniques, that have been used to perform the survey of the two bridges and the surrounding areas, riverbed included, hereafter briefly listed.

In identifying the most appropriate measurement techniques for the metric documentation of the structures studied in this work, it was essential to consider the conformation of the bridges and the morphology of the surrounding land and, obviously, the presence of the Arno River. More specifically, the aspects that guided the design of the detailed survey were:

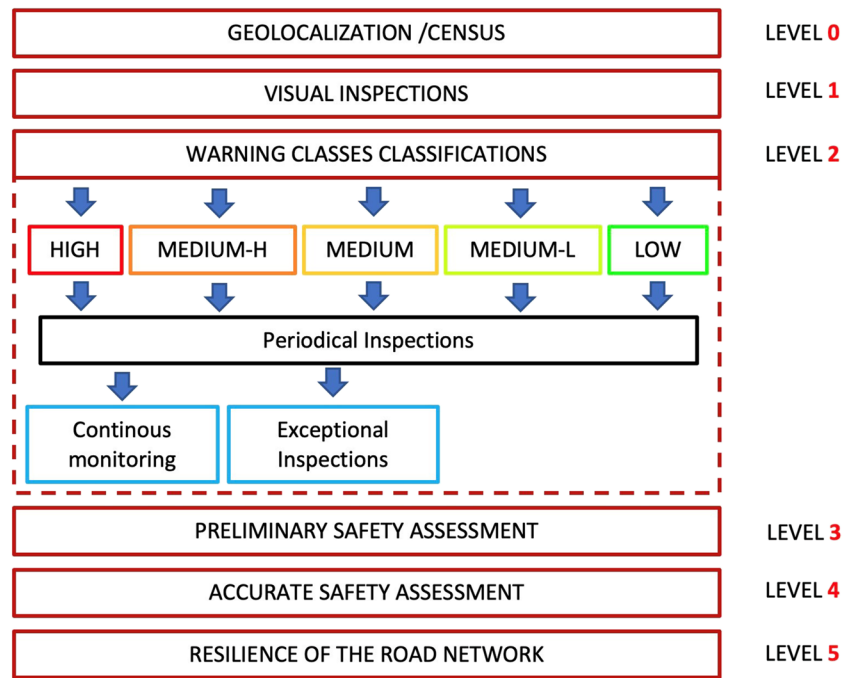
- the need to document, with a high level of detail, structures of considerable and preponderant size according to length;
- the presence of weeds along all the riverbanks and its consequence in performing an effective survey;
- difficult access to the central piers of the bridge and walkway and limited visibility of the intrados of the spans;
- the complexity of the bridge structure, consisting of parallel beams and transoms;
- the presence of an antenna of significant height (Lastra a Signa side) conditioning low-altitude drone flight paths.

Laser scanning was considered the most appropriate technique to survey the two structures, while photogrammetry by drone was more suitable to describe the overall area of interest.

Italian guidelines for the structural health assessment of bridges

The Italian Ministry of Infrastructures and Transport published unified guidelines for the safety evaluation and monitoring of bridges, the most recent update was issued by the ministerial decree 1st July 2022 (Ministero delle Infrastrutture e della Mobilità, 2022). The guidelines describe a multi-level

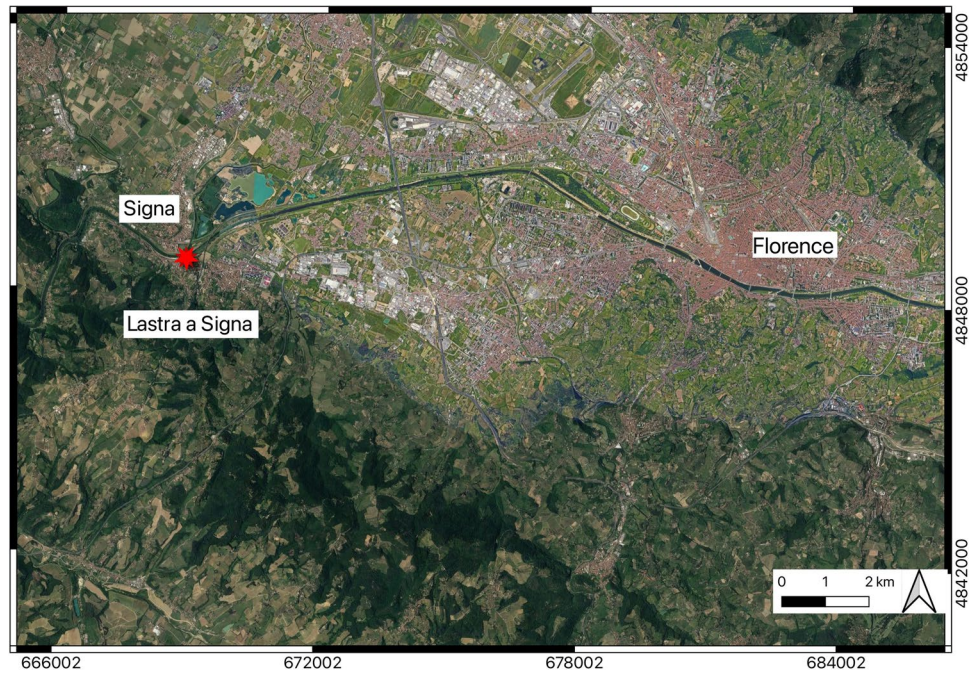
Fig. 1 Scheme of analysis levels. It describes the multi-level approach adopted by the MIT guidelines. Summarized from Ministero delle Infrastrutture e della Mobilità, 2022



Bridges inspection sheet: Reinforced Concrete															
Span		C6													
Beam		Tb													
N°	Description of defects	G	Extension K1			K1	Intensity K2			K2	N° Photo	PS	NA	NR	NP
			0.2	0.5	1		0.2	0.5	1						
1	Passive Dump	1	X			0.2			X	1	40				
2	Active Dump	3		X		0.5			X	1	40				
3	Drainage	3				0				0					X
4	Concrete Spalling	3	X			0.2			X	1	39				
5	Concrete Spalling (Headed)	4			X	1			X	1	39				
6	Water stagnation	2				0				0				X	
7	Caissons water stagnation	4				0				0			X		
8	Concrete honeycombs	2				0				0					X
9	Concrete detachment	2	X			0.2			X	1	35				
10	Reinforcement corrosion	5	X			0.2		X		0.5					
11	Cracks in correspondence of brackets	2	X			0.2		X		0.5					
12	Spider Web Cracks	1				0				0					X
13	Diagonal cracks	5				0				0				X	
14	Transversal Cracks	5				0				0					X
15	Longitudinal Cracks	2	X			0.2	X			0.2	40				
16	Cracks / beam detachments	3				0				0					X
17	Uncovered stirrups	3	X			0.2		X		0.5	12				
18	Broken brackets	4				0				0				X	
19	Degraded recovery	1				0				0					X
20	Impact damages	4				0				0					X
21	Deformed Longitudinal reinforcement	5			X	1	X			0.2	24				
22	Defects on the Gerber joints	5				0				0			X		
		Detected degradation index:									15%				
		Potential degradation Index (undetectable aspects):									18%				

Fig. 2 Defect sheet for reinforced concrete beams

Fig. 3 Satellite map of the study area. Red star = Walkway and Road Bridge. Coordinates unit = meters

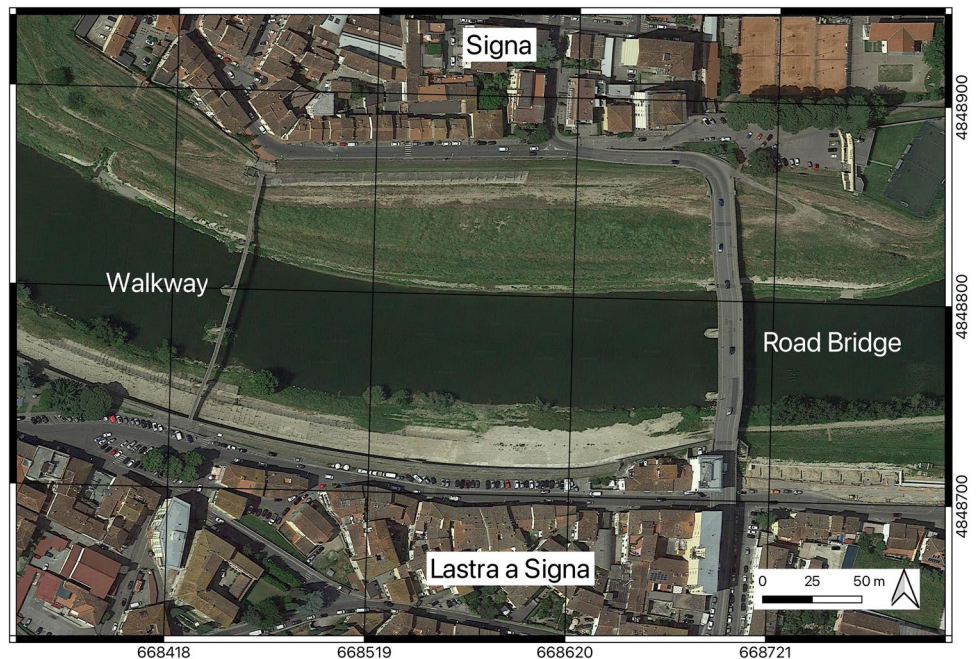


approach to knowledge of the structures and aspects influencing possible risk sources (Buratti et al., 2021), aiming to highlight which bridges require urgent interventions, detailed assessments, and rehabilitation. Obviously, the higher the inspection level, the higher the commitment needed in both economic and technical terms.

Multi-level approach

The multi-level approach allows to define a priority for monitoring and maintenance activities and to select the bridges

Fig. 4 Orthophoto of the study area. Bridges linking Lastra a Signa and Signa municipalities. Coordinates unit = meters



that need more detailed analyses foreseen by the other levels. (Beltrami et al., 2021; Buratti et al., 2021; Zambon et al., 2017). Applying the first three levels (Fig. 1), the whole infrastructural asset can be quickly screened.

The approach consists of six levels of analysis:

- Level 0, constructing a database, collecting information about all the bridges.
- Level 1, performing visual inspections to verify and update the database with information about geometrical and structural features of bridges.

Fig. 5 Walkway, upstream view

- Level 2 allows the classification of the bridges inspected in the previous level in terms of the “warning class.”
- Level 3 performs a preliminary safety assessment, thus getting a quick evaluation of the bridge’s safety.
- In level 4, the analyses become more complex and detailed. This level foresees the performing of an accurate safety level evaluation.
- Level 5 requires a resilience analysis of the road network; it is reserved to high importance bridges.

Levels 0, 1, and 2 must be applied on all the bridges; the evaluations are, therefore, on a territorial macro-scale. Level 2 analysis defines a class of attention (CoA) for each bridge: it is a function of hazard, vulnerability, and exposure factors, and it is classified as high, medium-high, medium, medium-low and low.

Each CoA corresponds to certain consequent actions, in terms of investigations, monitoring, assessments. Applying the other three levels (levels 3, 4, and 5) depends on the classification results; subsequent analyses can be planned according to practical necessities.

As can be seen from Fig. 1, periodical inspections and continuous monitoring are requested for level 2 warning class classification.

Level 3 and level 4 preliminary and accurate safety assessments may require continuous monitoring. In general, monitoring, inspections and geo-localisation are tasks that geomatic techniques and instruments can profitably support.

Defect sheet

Visual inspection is a traditional method of collecting information about the bridge’s condition. During the bridge service, the inspections are performed by qualified inspectors, who formulate judgments based on direct observation of the structure.

The subjectivity of expert opinions, however, influences this activity. Moreover, the frequency and accuracy of bridge inspections may influence future maintenance activities.

Some defects that can be perceived through visual inspection are reinforcement corrosion, uncovered stirrups, damp spots, and concrete cover spalling. Fig. 2

Fig. 6 Walkway, detail of concrete corrosion



Fig. 7 Walkway, diffuse concrete corrosion

shows a defect sheet extensively used to perform visual inspections.

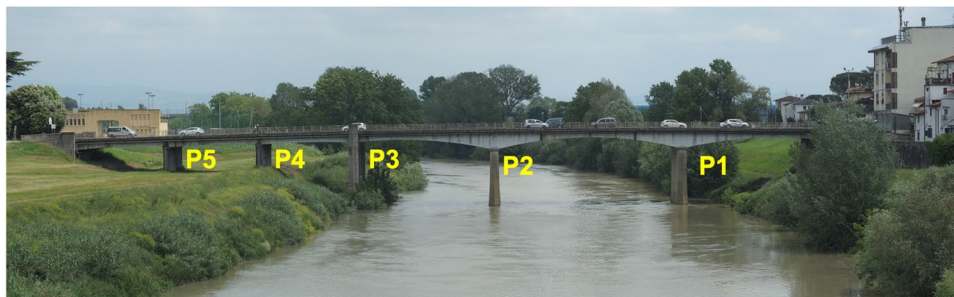
The defects description is linked to various photos technicians take during field surveys. A coefficient value is assigned to the identified defects, and a detected degradation index is calculated.

Case study

The case study here reported concerns the two structures which cross the Arno River between the municipalities of Lastra a Signa and Signa (Italy): a road bridge and a pedestrian walkway (Figs. 3 and 4).

Both were realized with reinforced concrete structures after World War II. The pedestrian walkway (Fig. 5) was built on the preexisting masonry bridge

Fig. 8 Ponte sull'Arno—view from downstream



blown up by the Germans in 1944, of which, in some points, some witnesses remain. The walkway consists of a single reinforced concrete beam supported by five piles, two founded on the ground and three in the water. Despite its length of over 120 m, it has a width of less than 2 m, which is relatively narrow. The structure is accessed via two flights of stairs from roads along the river, Via dello Stadio (Municipality of Signa) e piazza Guido Andrei (Municipality of Lastra a Signa). The walkway structure presents various deteriorations, such as reinforcement corrosion and uncovered stirrups (Figs. 6 and 7). The extrados has bitumen flooring and parapets with metal structures.

The “Ponte Nuovo sull’Arno” (Fig. 8) was blown up by the retreating Germans in 1944 and then rebuilt in 1948 near the original location of a medieval bridge (1120 AD). It has a reinforced cement concrete structure with the largest span of Gerber type; it is carried by five piles, different in shape and size, of which two (P1, P2) are entirely in the water, two on the ground (P4, P5) and one (P3) right on the riverbank. The bridge piles, like the walkway, rest on foundation plinths.

The structure consists of parallel beams with exposed crosspieces. The first three spans, crossing the river, are supported by Gerber beams. Near the side wall on the Lastra a Signa side, there is a sewer pipe. The bridge structure has various deteriorations and, over time (Figs. 9 and 10), has been reinforced with two series of bolted steel ties longitudinally and transversely. The extrados of the bridge has a bitumen flooring, with two central lanes reserved for cars flanked respectively by sidewalks, with a similar finish and parapets with a metal structure. The riverbanks are shaped in steps.

Surveying activities

Georeferencing and control network

The surveyed subjects are within a rather extended area. The reference system of such a sized survey is supposed to be:



Fig. 9 Ponte sull'Arno, series of bolted steel ties

- unambiguous, to coherently georeferencing the surveyed data;
- stable over time to enable periodical monitoring;
- adequately accurate to ensure the reliability of data analysis results;
- well documented to allow for switching amongst different reference systems.

To this purpose, a control network (Fig. 11) has been designed to cover the entire study area. It is composed of 12 vertexes, each one firmly materialized.

The network vertexes were materialized on the bridges' shoulders and in correspondence with the piles; a forced-centering system was used to ensure the instruments' best stability and avoid errors deriving from the measurement of



Fig. 10 Longitudinal and transversal bolted steel ties

instrumental heights. Satellite receivers (GNSS) and Total Stations (TS) conducted an integrated topographic survey.

A vertex was fixed in a barycentric position within the survey area, and its coordinates were adjusted considering the baselines (acquired for 2 h and 25 min each) of three GNSS permanent stations (IGM2, CALA, EMNS), with a maximum length of about 13 km (Fig. 12).

To assess the results, 3D RMS on baselines can be considered (their values range from ± 1 to ± 1.4 cm). Using two GNSS Trimble R10-2 receivers with a rover acquisition time of 8 minutes, the coordinates of all the network vertexes were post-processed. The acquisition time was set considering the limited lengths of baselines between the network points and the barycenter vertex (Fig. 13).

The acquisition time was set based on previous experiences; the results obtained by the independent measurements by total station confirm the effectiveness of the approach adopted.

The geographical coordinates of the network vertexes have been calculated in the Geodetic Reference System ETRS89-ETRF2000 (epoch 2008.0), which is materialized in Italy through the national dynamic network *Rete Dinamica Nazionale* (RDN).

In producing large-scale (or high accuracy) technical cartography both the deformations produced by the adopted map projection (m_d) and the effect produced by the distance of the measurements on the ground with respect to the reference surface (k , commonly referred to as “height deformation”) must be taken into account, in order to define an optimal cartographic representation, i.e., to maximize congruence between distances measured in the field and the corresponding cartographic distances.

Therefore, “rectilinear” or “isometric” coordinates were determined based on an ad hoc defined Gauss projection, with the central meridian at longitude of $11^\circ 5' 40''$ (passing through the barycentric vertex 8500); false easting and false northing values are applied to ensure X- and Y-values positives and to reduce the range of X- and Y-coordinate values; no scale factor has been applied (scale factor = 1).

Deformations affecting maps are related to the projection itself and to the ellipsoidal height of the site. The cartographic deformation is expressed by (1).

$$m_d = 1 + \frac{1}{2} \cdot \Delta\lambda^2 \cos^2\varphi \quad (1)$$

$\Delta\lambda$ = difference in longitude respect to the central meridian

φ = latitude

Considering the map projection adopted, since the central meridian is passing through the barycenter of the site (where $\Delta\lambda = 0$), cartographic deformation can be neglected ($m_d = 1$).

Considering the deformation due to the ellipsoidal height of the site, it is expressed by (2).

Fig. 11 Orthophoto with control network's vertexes



$$k = 1 + \frac{h}{R} \tag{2}$$

h = ellipsoidal height
 R = radius of curvature

The survey area has an ellipsoidal height of about 80 m; therefore, the deformation is about 12 ppm, also corresponding to the total deformation expected in the map projection.

Considering this value to be acceptable with respect to the objectives of the survey, it was deemed appropriate not to introduce a scale factor to counterbalance the deformations.

To validate the results, they were compared with the coordinates obtained from the least-squares adjustment of the same control network measured by a TS Leica TCRA1202 (Fig. 14) with angular accuracy $1\sigma = \pm 0.6$

mgon, and the accuracy of distances measured with a reflecting prism $\pm 2 \text{ mm} + 2 \text{ ppm}$. The least square adjustment provides error ellipses for all the vertices with a semimajor axis lower than 7 mm.

Considering the most distant vertex pair measured by the two independent processes, the maximum planimetric distance was 5 mm, becoming lower when approaching the center of the area.

The *Verto* software, developed by the Italian Geographic Military Institute (Istituto Geografico Militare Italiano, IGMI), was used to transform ellipsoidal heights into orthometric heights. The heights were then calculated for all vertexes based on trigonometric levelling. The obtained results allow for considering the control network as a reliable reference for future surveys and monitoring operations in the area.

Fig. 12 View of the baselines

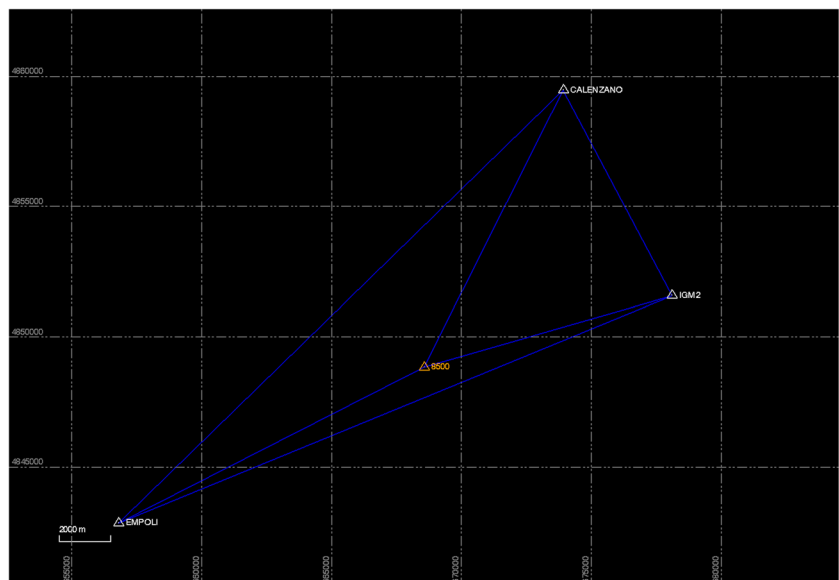




Fig. 13 GNSS measurements

The control points for the laser scanner and photogrammetric survey were then determined by topographic measurements starting from the control network vertexes (Fig. 15); since some targets were visible from more than one topographic vertex, they were measured independently from each of them, and the coordinates obtained subsequently compared, therefore confirming the accuracy expected for control points.

Photogrammetry—planimetry and orthophoto of the study area

The resolution of a photogrammetric survey depends on the distance from the camera to the object, given a specific camera model, and neglecting some project parameters such as overlapping, flight plan, and control points distribution. The availability of RPAS with a high-resolution optical camera allows

for maintaining almost constant distance with respect to the object and therefore investigating hardly accessible structures by flying. Performing regular flight paths, and parallels to the main surfaces, allows for obtaining almost complete documentation of the structures (Lo Brutto et al., 2014) and detecting construction materials through elaborating images (DeGol et al., 2018).

A photogrammetric survey of the area between the two bridges was performed with a DJI Phantom 4 drone. The flight plan (Fig. 16) was constrained by a tall building with a mobile phone antenna on a roof near the road bridge on the Lastra a Signa side. For this reason, it was necessary to fly at an altitude of about 35 m AGL, which corresponds to a GSD of about half a centimeter, making 13 strips in the north-south direction with 80% forward overlap and 60% side overlap. The survey was carried out with a nadir camera, taking 308 photos.

Before processing images according to the photogrammetric workflow, all the photos were edited to enhance them. The photogrammetric workflow involves inserting control points to orient and scale the model through the bundle block adjustment. For this, 29 ground control points (GCP) and 21 check points (CP) were used, considering both the targets arranged on the ground and some targets positioned on the bridges for the alignment of the scans but also clearly visible in the aerial photos. The 3D RMS error is 1.2 cm (1.1 cm on XY and 0.5 on Z) on the GCPs and 1.8 cm (1.2 cm on XY and 1.3 cm on Z) on the CPs.

Images framing only the river have a uniform texture, thus avoiding features and tie point recognition; therefore, their orientation failed.

Laser scanning—bridge survey: 3D models and 2D drawings

For DPC obtained by laser scanning, resolution mainly depends on settings, being in any case limited by the technical characteristics of the instrument itself; the range also depends on it, with significant differences according to the technology adopted for distance measurement (time of flight

Fig. 14 TS control network measurements



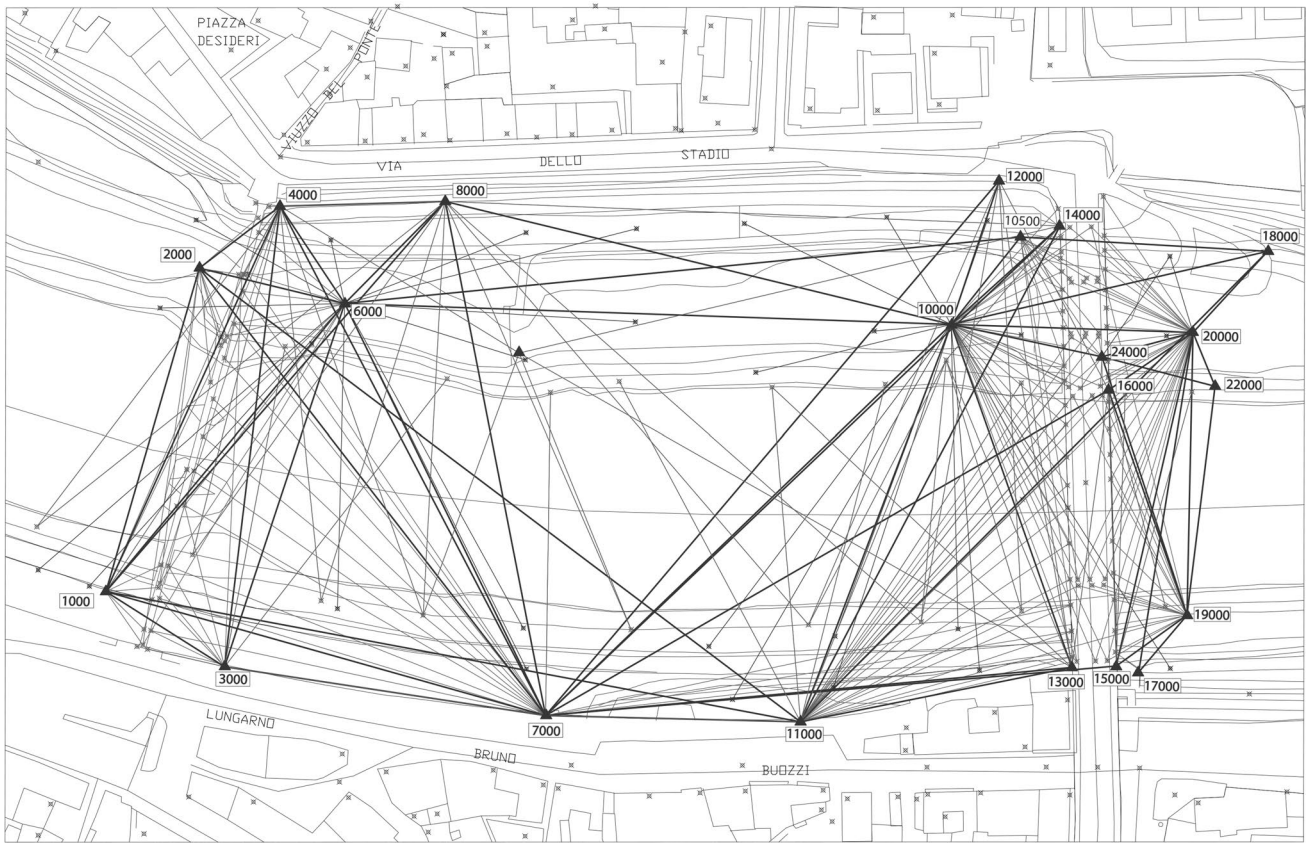


Fig. 15 Scheme of the topographic measures carried out for determining the targets used for the control and referencing of laser scanning and photogrammetric surveys

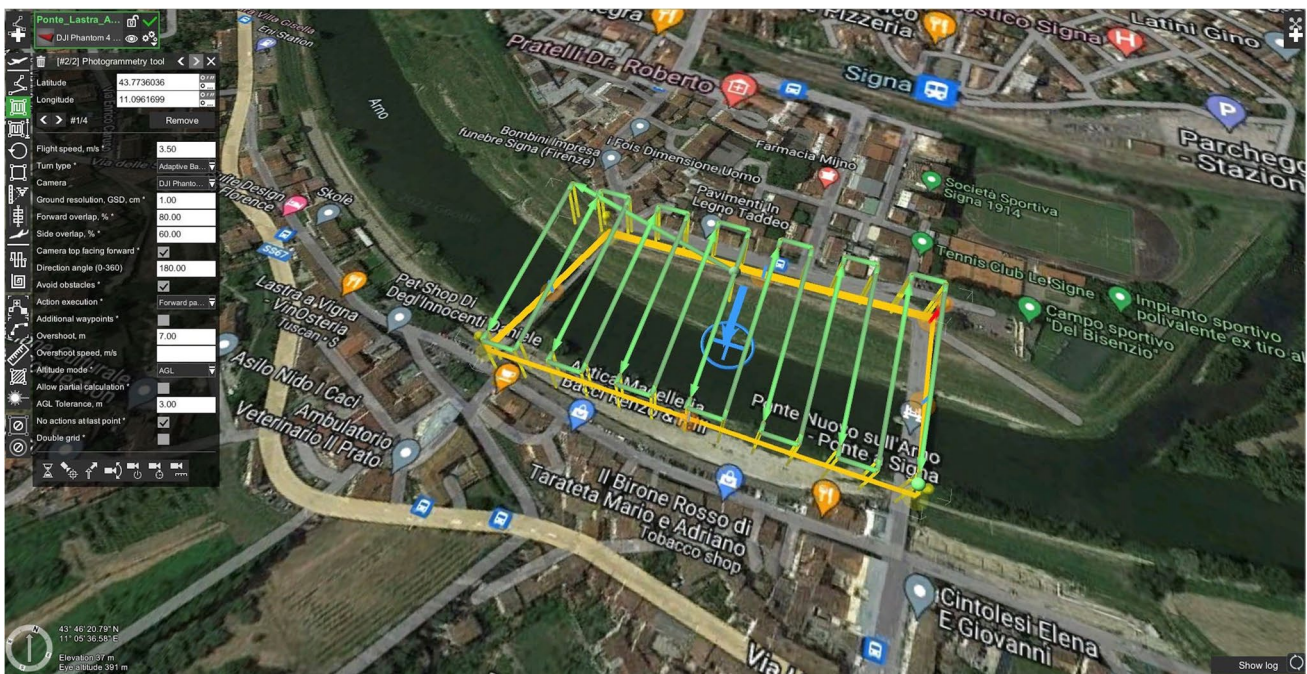
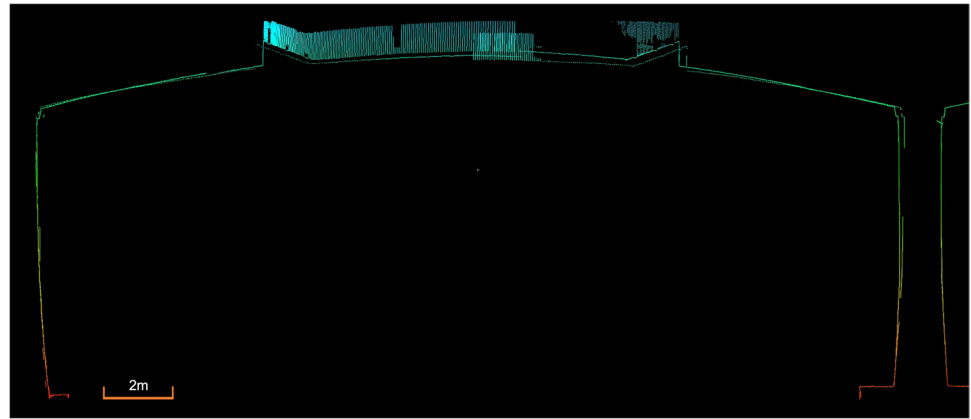


Fig. 16 Flight plan of the photogrammetric survey (UGCS software interface)

Fig. 17 Profiles from the different acquisitions: the section on the span shows a misalignment of about 30 cm



or phase shift). Working with TLS, it is often possible to acquire geometric information and photographs from which to derive the RGB values associated with the points, even if this significantly increases the field's operating time.

However, when obtaining chromatic information of relevant quality, it is essential to pay close attention to the lighting conditions—a challenging aspect when operating outdoors, acquiring data in all directions (and therefore always facing the sun, unless there are lucky overcast days). Depending on the scene to be scanned, the geometric resolution achievable by the scanner may be higher than the corresponding photographic one (Tucci et al. 2017), thus suggesting adopting non-RGB visualizations to support, for example, decay interpretation and crack pattern reading. A relevant parameter to characterize a laser scanner survey, although difficult to quantify, is the completeness of the documented surfaces

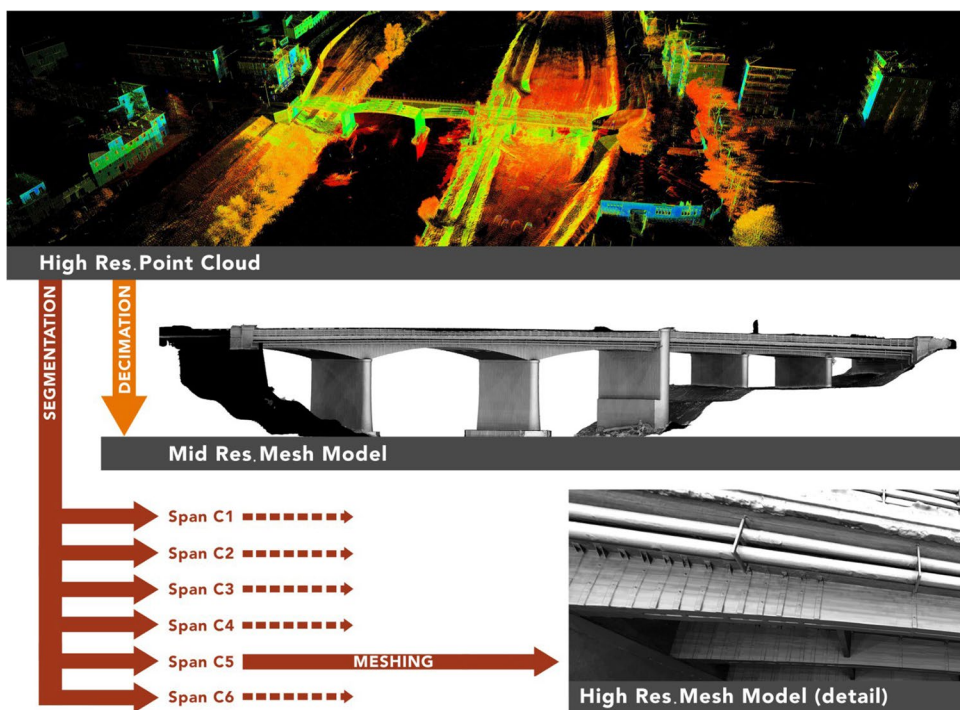
of interest, which is related to the morphometric complexity of the object to be surveyed, the number of scans performed, and the choice of scan position. The river constitutes a critical element for the need to position the laser scanner near the central spans of the structure to obtain a complete 3D model with uniform resolution.

The laser scanner survey was performed using a Z+F 5010C scanner. 65 scans were acquired, with a resolution of 3 mm at 10 m. The scans of the bridge were made along the two sides: one set at less than 10 m and one at less than 2 m from the projection of the bridge to the ground; this made it possible to acquire the undercut elements of the crowning frames hidden by the existing plants. Further scans were made under the spans with a regular pattern to detect the beams' and transoms' horizontal and vertical faces. At the time of the survey, the water level was low enough to leave the foundation of the



Fig. 18 Raw orthophoto of the surveyed area (300 m in length and 170 m in width)

Fig. 19 Mesh models elaboration



piles partially out of water, thus allowing the scanner to be positioned on them. Thanks to an inflatable boat, it was also possible to reach the central pile, thus homogeneously completing the bridge documentation. All scans were carried out in full-dome mode; this enabled good coverage on both banks, except for the central area, which is almost equidistant from the two bridges. The scans were registered thanks to 27 targets on the walkway and 53 targets on the bridge curbs and pillars; all the targets were measured by a total station from the control network vertexes (when it was possible from more than one). The scan registration process requires roto-translation of each scan based on target correspondence, and a further ICP optimization. The software used is Cyclone by Leica Geosystems, which does not provide relevant statistics. Scan alignment can be therefore assessed by considering the

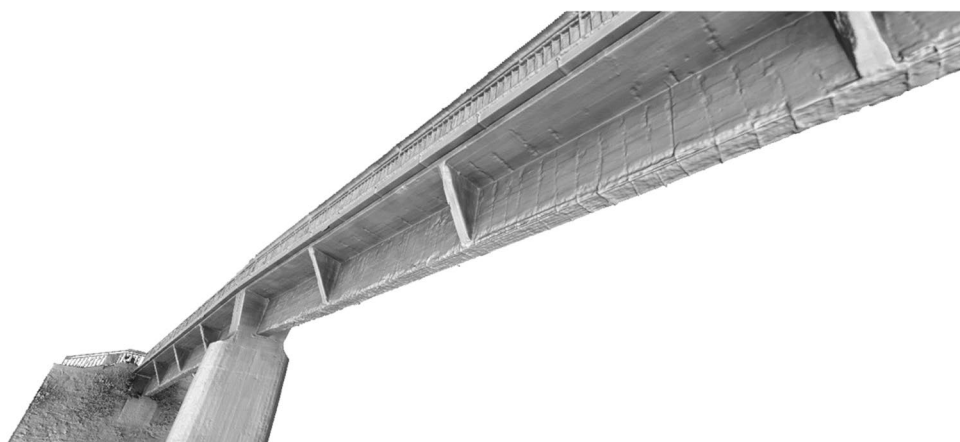
residual distances between corresponding targets (in the case study always lower than a cm) and the mean error after ICP between overlapping scans (lower than 3 cm).

A model of 5.5 billion points with an average resolution of about half a centimeter was obtained.

Riverbed bathymetric survey

In Bridges Health Assessment, and more in general for structural and archaeological inspections, bathymetric survey can play a crucial role, especially in such contexts where erosion on the abutments is acting, e.g., scour (Larrarte et al., 2020; Zheng et al., 2018), or in case the presence of historical foundations somehow drives the bridge’s stability (Bento et al., 2020; Chen et al., 2021; Zheng et al., 2020). Several bathymetric survey systems and techniques are currently available

Fig. 20 Mesh model of the walkway



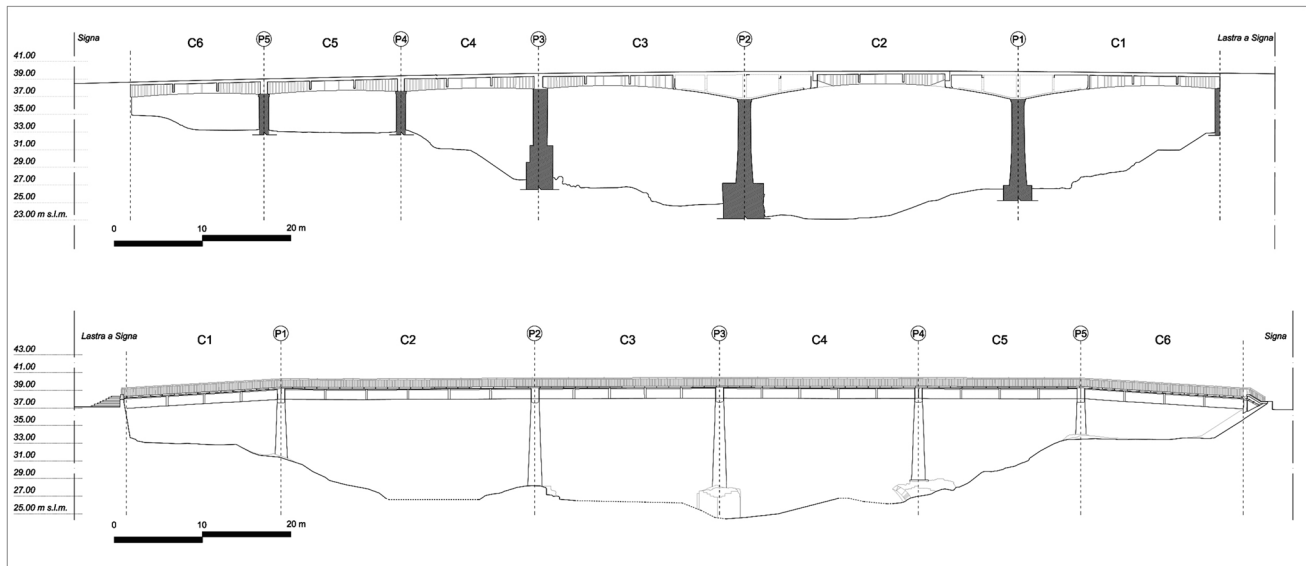


Fig. 21 Bridge longitudinal section (top) and aerial walkway Est elevation (down), original drawings in 1:100 scale

for deep (Purser et al., 2018) and shallow waters (Suhari et al., 2017), marine (Mugnai et al., 2019b) and river applications (Huizinga, 2010; Legleiter & Harrison, 2019), autonomous (Gelli et al., 2018) and manned vehicles (Terracciano et al., 2020), remote (Mandlbürger, 2020; Salameh et al., 2019), and proximal sensing (Amoroso & Parente, 2021; Giordano et al., 2015). In the present case study, the riverbed and underwater structures were mapped with an MBMS, which emits a multidirectional radial beam to obtain information within a fan-shaped swath. A MBMS integrates several components: a multibeam emitter system (MBES), an inertial navigation system (INS) and a computer for data collection and processing. GNSS antennae and INS provide positioning and measure the vessel’s sway, pitch, roll and heading (and thus the MBES).

The presence of a bathymetric survey, which has been integrated with GNSS, Photogrammetry and Laser Scanner surveys, can also be considered as a state of the art advancement (Rizzo & Enshaiean, 2021).

To perform the riverbed and underwater structures documentation in the study area, the MBMS has been installed on an inflatable boat, able to operate with a limited draft. A laser scanner (HDS 7000, by Leica Geosystems) was also installed on the boat as a profilometer. The processing of the detected data was entrusted to a private company, which delivered one DPC relating to the bathymetric survey and one relating to the out-of-the-water made with the profilometer.

The referencing was carried out by applying the ICP algorithm between point clouds, considering the TLS survey of the bridges as a reference. Validation of the obtained results was planned by determining a series of large format targets along the banks, but the resolution of the out of the water data does not allow for adequate recognition.

The overlap of data acquired in various acquisitions highlights critical misalignments between the different profiles (on average of the order of 15–20 cm, but with maximum values up to about 50 cm), which are negligible in

Fig. 22 Detail of riverbanks section profiles: the upper profile, acquired in October 2019 and the lower in January 2020

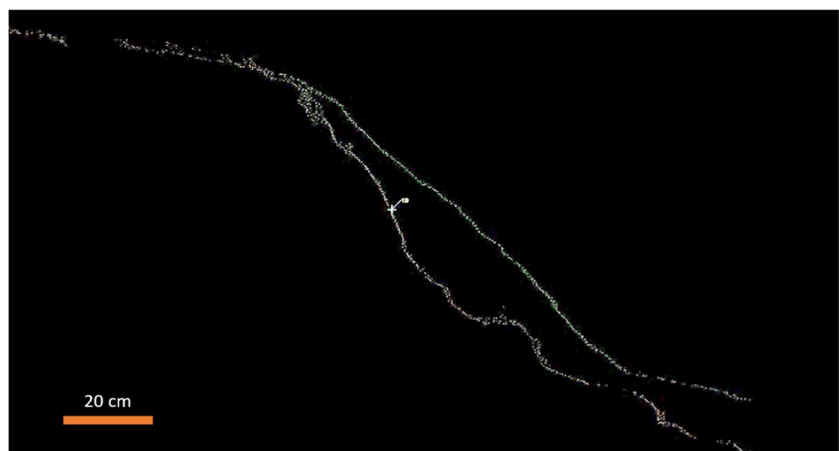




Fig. 23 TLS survey

the modelling of the banks, but which prevent the correct analysis of bridge structures (Fig. 17).

The acquisition resolution has been appropriately increased in the areas of most significant interest mapping the riverbed, up to a few centimeters away amongst various profiles, and even lower between the points of the same profile. In the other areas, the resolution is about 25 cm.

Discussion

Thanks to the adequate control network, described in the previous section, the comparability over time of the results obtained through the survey campaigns is guaranteed. Even if the GNSS measurements release the reference system

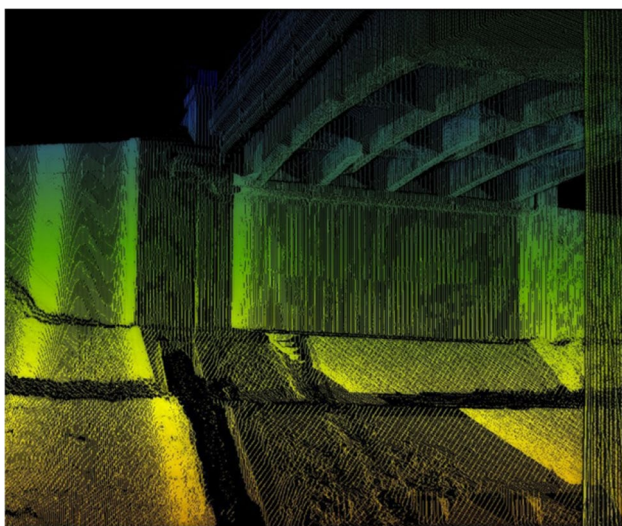


Fig. 24 Survey with profilometer mounted on the boat

definition from its materialization on the ground or artefacts, the detailed survey or the observation collected to monitor the structures are, in any case, carried out with classic topographic systems or that rely on them through control points.

The availability, around the structures to be monitored, of an adequate number of vertexes, stably materialized and determined with adequate accuracy, therefore constitutes a good investment, with evident returns over time in terms of efficiency and effectiveness.

Each of the performed surveying activities, namely, laser scanning, GNSS, photogrammetry, and bathymetry, allow for producing a specific output that cooperates in building a complete and reliable documentation of the surveyed area, namely the orthophoto with 10 mm GSD (Fig. 18), the 3D point clouds and the related elaborations such as surface models, and 2D CAD drawings.

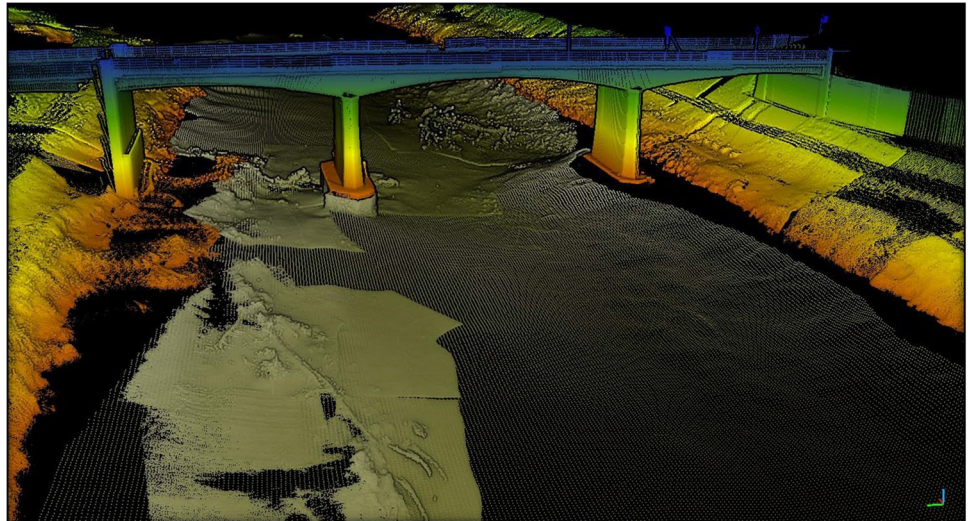
On the laser scanning survey

Once obtained the 5.5 billion points model, several subsequent steps were required to process point clouds and to obtain surface models (meshes) (Fig. 19). Point cloud segmentation and cleaning, filtering, and noise reduction, unnecessary mesh portions removal, and progressive decimation. Further elaboration of the bridges' DPCs led to mesh with different resolutions; particular attention has been paid to the meshing process (made with the Surface Reconstruction Poisson algorithm (Kazhdan et al., 2006)), to preserve a high level of detail and to ensure the excellent manageability of the models simultaneously.

As the walkway is small, only one mesh model of the entire structure was created (Fig. 20). The mesh models obtained have sufficient resolution to read details such as the footprint of the formwork, the degradation of the surfaces and the beam's reinforcement ties. They can therefore be considered as digital references of the actual artefacts, on which it is possible to read highly detailed information (as in on-site visual or photographic inspections), having at the same time an overall view of the bridge structure. Several systems have been developed over time, albeit only as prototypes, allowing specialists to interact with a 3D model and annotate vector and raster information directly on the model surface, especially for managing restoration projects (Apollonio et al., 2018; Soler et al., 2017).

3D models offer the advantage of realistic visualization and permit interactive exploration, with pan and zoom on the details. However, design processes related to built heritage are generally still based on 2D drawings, which, although synthesizing some information, have the advantage of offering an overview and, above all, of quickly providing the necessary size information. For the bridge and the walkway, several 2D CAD drawings were plotted: a floor plan, a view of the deck from the bottom up, a plan of the pylons, elevations, and some longitudinal and cross sections (Fig. 21).

Fig. 25 Multibeam scanning of the riverbed with increased resolution in correspondence with elements of interest (from a minimum resolution of about 25 cm to a maximum of a few cm)



The processes measurements aimed at BHM according to the highest safety assessments established by Italian law require highly accurate observations to recognize even minor effects of structural stresses. However, in a dynamic situation, such as a riverbed, even macroscopic variations are evident due to phenomena of no exceptional nature. For example, a new, partial laser scanner survey campaign detects, on the banks, the erosive effects of the intervening flood (Fig. 22).

On the profilometer survey

As mentioned above, only qualitative assessments are possible on the data collected by the rubber dinghy in this case study, for which descriptive reports of the processes performed are unavailable. It is evident that a mobile mapping system allows significant speed up the acquisition in the field, albeit with limited accuracy and resolution, when comparing these characteristics with those of static systems. In the case study presented, two situations can be distinguished:

- A survey of the riverbanks and the area immediately facing the river
- A survey of structures such as bridges and walls

In the first case, the resolution can be considered adequate for simplified modelling and helpful in supporting hydraulic engineering studies, for example. As for the completeness of the model, it is very good along the banks, in the sloped areas immediately adjacent to the river, where, on the contrary, the TLS survey is lacking. On the other hand, the effect of the point of view slightly raised on the water surface must be considered, since it defines extensive lack of data on the higher pseudo-horizontal surfaces. Misalignments between profiles recorded in consecutive passages

and the poor resolution on targets can be optimized by following more suitable data acquisition and post-processing procedures. Regarding the bridges' 3D documentation, the resolution of scans acquired by the profilometer is too poor to identify the bridges' main structural elements and does not allow for measuring their size on the 3D model: on the bridge main girders the profilometer resolution is about 2 cm along the profile, with profiles spaced about 6 cm. Figs. 23 and 24 show acquisitions made by TLS and profilometer, respectively, of the shoulder of the bridge towards Lastra a Signa, where the sewer pipe is also visible.

On the bathymetric survey

The bathymetric survey made it possible to document the course of the riverbed and the submerged structures (Fig. 25).

It allowed the assessment of the undermining that occurred at the piers' foundations (more relevant in the central pier of the bridge) and the possibility of recognizing the presence of stranded trunks on the riverbed, which are not visible from out of the water. The transport of significant vegetation constitutes a critical element in major floods, as it can obstruct the river's course.

At the walkway piers, the shallow water level, and the presence of currents, limited the boat's maneuverability and prevented it from crossing the structure, also due to the remains of partially emerged structures relating to the ancient bridge.

Conclusion

Resolution and completeness of the produced models, both concerning the structures and their surrounding context, allows them to be considered good support for assessing

the conservation status of the artefacts. They allow to know the size of the structures and their elements, identify the damaged parts, and quantify the extent and severity of decay effects. Moreover, they play a crucial role in analyzing the current state and the damage that occurred in the past; they can also support planning, monitoring and interventions.

The paper illustrates the articulated workflow adopted for the metric documentation of the various elements relevant to the study: the structures of the bridges, the riverbanks and the artifacts that stand on them, the riverbed, and the submerged structures. Only the integration of different survey techniques (photogrammetry, laser scanning, bathymetric survey) allowed to balance the strengths and weaknesses of each.

The role of the topographical control network is essential and twofold, both to consistently align all recorded data and to ensure the comparability of data collected in subsequent survey campaigns, i.e., supporting monitoring activities. Therefore, the models produced with geomatic techniques constitute the geometric support capable of evolving for informative and interdisciplinary annotations and considerations and for sharing in an interdisciplinary project. Other than for measuring and documenting dimensions and shapes, geomatics contributes to crucial data for characterizing and monitoring, over time, the risk associated with structure degradation. The ongoing studies envisage interesting possibilities for the development of automatic methods, allowing to design the quality of recorded data before their collection, e.g., systems supporting image acquisition path from handheld, UAV-mounted, and crane cameras (Tuttas et al., 2016), to optimize TLS survey by defining the best sensor configurations to improve the density and accuracy of DPC (Zhang et al., 2016), mobile mapping with ground rovers systems (Wetzel et al., 2022).

The awareness of guidelines for safety evaluation (Santarsiero et al., 2021), which allow for more conscious choices in terms of survey planning and data analysis, is a noticeable add value.

A future development could assess the effectiveness and the advantage of integrating such surveying techniques with the most common structural health assessment methods. Such a synergy could enhance performances, in terms of time and accuracy, of assessing bridges' stability.

Acknowledgements The on-the-field survey was supported by Massimo Piazzesi (Trimble Geospatial) and designed by Alessandro Conti and Lidia Fiorini, who also performed in-field activities and 3D data elaboration. Adele Meucci also participated in 2D drawing sessions. Trimble Geospatial (Massimo Piazzesi) supported the GNSS survey, Filippo Fiaschi participated in the project as drone pilot and Paolo Aminti designed and measured the GNSS and TS control network and coordinated the related computation and adjustment. Oikos engineering s.r.l. was commissioned to undertake the bathymetric survey.

Funding Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement. The project was partially funded by the Municipality of Lastra, and of Lastra a Signa.

Data Availability The data that support the findings of this study are not openly available and are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Adamopoulos E, Rinaudo F (2021) Close-range sensing and data fusion for built heritage inspection and monitoring—a review. *Remote Sens (Basel)* 13(19):3936
- Alani AM, Tosti F, Ciampoli LB, Gagliardi V, Benedetto A (2020) An integrated investigative approach in health monitoring of masonry arch bridges using GPR and InSAR technologies. *NDT&E Int* 115:102288
- Alba MI, Barazzetti L, Scaioni M, Rosina E, Previtali M (2011) Mapping infrared data on terrestrial laser scanning 3D models of buildings. *Remote Sens (Basel)* 3(9):1847–1870
- Amoroso PP, Parente C (2021) The importance of sound velocity determination for bathymetric survey. *Acta Imeko* 10(4):46–53
- Apollonio FI, Basilissi V, Callieri M, Dellepiane M, Gaiani M, Ponchio F, Rizzo F, Rubino AR, Scopigno R (2018) A 3D-centered information system for the documentation of a complex restoration intervention. *J Cult Herit* 29:89–99
- Baltsavias EP (1999) A comparison between photogrammetry and laser scanning. *ISPRS J Photogramm Remote Sens* 54(2–3):83–94. [https://doi.org/10.1016/S0924-2716\(99\)00014-3](https://doi.org/10.1016/S0924-2716(99)00014-3)
- Banfi F, Brumana R, Roascio S, Previtali M, Roncoroni F, Mandelli A, Stanga C (2022) 3D heritage reconstruction and Scan-to-HBIM-to-XR project of the tomb of Caecilia Metella and Caetani Castle, Rome, Italy. *Int Arch Photogramm Remote Sens Spat Inf Sci* 46:49–56
- Bao Y, Tang Z, Li H, Zhang Y, Agdas D, Rice JA, Martinez J, Lasa I, León-Robles CA, Reinoso-Gordo JF, González-Quñones JJ, Borin P, Cavazzini F, Morgenthal G, Hallermann N, Kersten J, Taraben J, Debus P, Helmrigh M et al (2021) Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. *J Perform Constr Facil* 30(3):1–10. <https://doi.org/10.3221/IGF-ESIS.46.37>
- Barazzetti L, Banfi F, Brumana R, Gusmeroli G, Oreni D, Previtali M et al (2015) Bim from laser clouds and finite element analysis: combining structural analysis and geometric complexity. *Int Arch Photogramm Remote Sens Spat Inf Sci* 5:W4
- Barrile V, Candela G, Fotia A, Bernardo E (2019) UAV survey of bridges and viaduct: workflow and application. In: *International Conference on Computational Science and Its Applications*. Springer International Publishing, pp 269–284
- Bazzocchi F, Restuccia L, Ferro GA (2018) Considerations over the Italian road bridge infrastructure safety after the Polcevera viaduct

- collapse: past errors and future perspectives. *Frat Ed Integrita Strutt* 12:400–421. <https://doi.org/10.3221/JGF-ESIS.46.37>
- Beltrami C, Bianchi S, Cervio M, Anghileri M, Felicetti R, Quattrone A, Chiara M, Salza B, Masala D (2021) In Bridge visual inspections: Experience of local authorities and the case study of the Corso Grosseto viaduct. In: *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations*. CRC Press, pp 3358–3364
- Bento AM, Gomes A, Viseu T, Couto L, Pêgo JP (2020) Risk-based methodology for scour analysis at bridge foundations. *Eng Struct* 223:111115
- Beshr AAE-W (2015) Structural deformation monitoring and analysis of highway bridge using accurate geodetic techniques. *Engineering* 7(08):488
- Brumana R, Oreni D, Cuca B, Binda L, Condoleo P, Triggiani M (2014) Strategy for integrated surveying techniques finalized to interpretive models in a byzantine church, Mesopotam, Albania. *Int J Archit Herit* 8(6):886–924
- Brutto L, Mauro G, A., & Meli, P. (2014) Uav platforms for cultural heritage survey: first results. *ISPRS Ann Photogramm Remote Sens Spat Inf Sci* 2(5)
- Buratti G, Celati S, Cosentino A, Gaudio D, Mazzatura I, Morelli F, Salvatore W (2021) The new guidelines of Italian Ministry of Infrastructures for the structural risk classification of existing bridges: genesis, examples of application and practical considerations. In: *International Conference of the European Association on Quality Control of Bridges and Structures*. Springer International Publishing, pp 835–844
- Catbas N, Avci O (2022) A Review of Latest Trends in Bridge Health Monitoring. In: *Proceedings of the Institution of Civil Engineers-Bridge Engineering*. Springer International Publishing, pp 1–40
- Chen B, Yang Y, Zhou J, Zhuang Y, McFarland M (2021) Damage detection of underwater foundation of a Chinese ancient stone arch bridge via sonar-based techniques. *Measurement* 169:108283
- Conti A, Fiorini L, Massaro R, Santoni C, Tucci G (2020) HBIM for the preservation of a historic infrastructure: The Carlo III bridge of the Carolino Aqueduct. *Appl Geomat* 14:1–11
- Corongiu M, Tucci G, Santoro E, Kourounioti O (2018) Data integration of different domains in geo-information management: a railway infrastructure case study. In: *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*
- Corr DJ, McCann DM, McDonald BM (2010) Lessons learned from marcy bridge collapse. In: *In Forensic Engineering 2009. Pathology of the Built Environment*, pp 395–403
- Dabous SA, Feroz S (2020) Condition monitoring of bridges with non-contact testing technologies. *Autom Constr* 116:103224
- DeGol J, Lee JY, Kataria R, Yuan D, Bretl T, Hoiem D (2018) FEATS: Synthetic feature tracks for structure from motion evaluation. In: *2018 International Conference on 3D Vision (3DV)*, pp 352–361
- Enright MP, Frangopol DM (2000) Survey and evaluation of damaged concrete bridges. *J Bridge Eng* 5(1):31–38
- Fan J, Saadeghvaziri MA (2019) Applications of drones in infrastructures: challenges and opportunities. *Int J Mech Mechatron Eng* 13(10):649–655
- Fawzy HE-D (2019) 3D laser scanning and close-range photogrammetry for buildings documentation: a hybrid technique towards a better accuracy. *Alex Eng J* 58(4):1191–1204
- Gagliardi V, Benedetto A, Ciampoli LB, D'Amico F, Alani AM, Tosti F (2020) Health monitoring approach for transport infrastructure and bridges by satellite remote sensing Persistent Scatterer Interferometry (PSI). In: *Earth Resources and Environmental Remote Sensing/GIS Applications XI*, vol 11534, pp 88–97
- Gaspari F, Ioli F, Barbieri F, Belcore E, Pinto L (2022) Integration of uav-lidar and uav-photogrammetry for infrastructure monitoring and bridge assessment. *Int Arch Photogramm Remote Sens Spat Inf Sci* 43:995–1002
- Gelli J, Meschini A, Monni N, Pagliai M, Ridolfi A, Marini L, Allotta B (2018) Development and design of a compact autonomous underwater vehicle: Zeno AUV. *IFAC-PapersOnLine* 51(29):20–25
- Giordano F, Mattei G, Parente C, Peluso F, Santamaria R (2015) Integrating sensors into a marine drone for bathymetric 3D surveys in shallow waters. *Sensors* 16(1):41
- Gu C, Rice JA, Li C (2012) A wireless smart sensor network based on multi-function interferometric radar sensors for structural health monitoring. In: *In 2012 IEEE Topical Conference on Wireless Sensors and Sensor Networks*. IEEE, pp 33–36
- He L, Reynders E, García-Palacios JH, Carlo Marano G, Briseghella B, De Roeck G (2020) Wireless-based identification and model updating of a skewed highway bridge for structural health monitoring. *Appl Sci* 10(7):2347
- He Z, Li W, Salehi H, Zhang H, Zhou H, Jiao P (2022) Integrated structural health monitoring in bridge engineering. *Autom Constr* 136:104168
- Huizinga RJ (2010) Bathymetric surveys at Highway Bridges Crossing the Missouri River in Kansas City. In: *Missouri, using a multi-beam echo sounder, 2010. Survey (US), Geological*
- Jiménez-Jiménez SI, Ojeda-Bustamante W, Marcial-Pablo MDJ, Enciso J (2021) Digital Terrain Models Generated with Low-Cost UAV Photogrammetry: Methodology and Accuracy. *ISPRS Int J Geo Inf* 10(5):285
- Kazhdan M, Bolitho M, Hoppe H (2006) Poisson surface reconstruction. In: *Proceedings of the Fourth Eurographics Symposium on Geometry Processing*, p 7
- Khedmatgozar Dolati SS, Caluk N, Mehrabi A, Khedmatgozar Dolati SS (2021) Non-Destructive Testing Applications for Steel Bridges. *Appl Sci* 11(20):9757
- Korumaz M, Betti M, Conti A, Tucci G, Bartoli G, Bonora V, Korumaz AG, Fiorini L (2017) An integrated Terrestrial Laser Scanner (TLS), Deviation analysis (DA) and finite element (FE) approach for health assessment of historical structures. A minaret case study. *Eng Struct* 153:224–238
- Kuras P, Owerko T, Ortyl Ł, Kocierz R, Sukta O, Pradelok S (2012) Advantages of radar interferometry for assessment of dynamic deformation of bridge. *Proceedings of the Sixth International IABMAS Conference*. Stresa, Italy, pp 885–891
- Larrarte F, Chevalier C, Battist L, Chollet H (2020) Hydraulics and bridges: a French case study of monitoring of a bridge affected by scour. *Flow Meas Instrum* 74:101783
- Legleiter CJ, Harrison LR (2019) Remote sensing of river bathymetry: Evaluating a range of sensors, platforms, and algorithms on the upper Sacramento River, California, USA. *Water Resour Res* 55(3):2142–2169
- Li H, Ou J (2016) The state of the art in structural health monitoring of cable-stayed bridges. *J Civ Struct Health Monit* 6(1):43–67
- Limongelli MP, Chatzi E, Anžlin A (2018) Condition assessment of roadway bridges: From performance parameters to performance goals. *Balt J Road Bridge Eng* 13(4):345–356. <https://doi.org/10.7250/bjrbe.2018-13.421>
- Lo Brutto M, Iuculano E, Giudice PL (2021) Integrating topographic, photogrammetric and laser scanning techniques for a scan-to-bim process. *Int Arch Photogramm Remote Sens Spat Inf Sci* 43:883–890
- Maizar M, Zhang L, Miramini S, Mendis P, Thompson RG (2017) Detecting structural damage to bridge girders using radar interferometry and computational modelling. *Struct Control Health Monit* 24(10):e1985
- Mandlbürger G (2020) A review of airborne laser bathymetry for mapping of inland and coastal waters
- Ministero delle Infrastrutture e della Mobilità (2022) Linee guida per la classificazione e gestione del rischio, la valutazione della

- sicurezza ed il monitoraggio dei ponti esistenti (p 40). Repubblica Italiana. <https://www.gazzettaufficiale.it/eli/gu/2022/08/23/196/sg/pdf>. Accessed 27 apr 2023
- Ministry of Infrastructures and Transports, 5 (2020) Ministerial Decree 578 on 17.12.2020. Adoption of Guidelines for the Classification and Management of Risk, the Safety Assessment and the Monitoring of Existing Bridges (pp 1–14)
- Mishra M, Lourenço PB, Ramana GV (2022) Structural health monitoring of civil engineering structures by using the internet of things: A review. *J Build Eng* 48:103954
- Mohammadi M, Rashidi M, Mousavi V, Karami A, Yu Y, Samali B (2021) Case study on accuracy comparison of digital twins developed for a heritage bridge via UAV photogrammetry and terrestrial laser scanning. In: Proceedings of the 10th International Conference on Structural Health Monitoring of Intelligent Infrastructure, SHMII, p 10
- Mugnai F, Lombardi L, Tucci G, Nocentini M, Gigli G, Fanti R (2019a) Geomatics in bridge structural health monitoring, integrating terrestrial laser scanning techniques and geotechnical inspections on a high value cultural heritage. In Brumana R, Pracchi V, Rinaudo F, Grimoldi A, Scaioni M, Previtali M, Cantini L (ed), *Int Arch Photogramm Remote Sens Spat Inf Sci* 42:895–900. <https://doi.org/10.5194/isprs-archives-XLII-2-W11-895-2019>
- Mugnai F, Ridolfi A, Bianchi M, Franchi M, Tucci G (2019b) Developing affordable bathymetric analysis techniques using non-conventional payload for cultural heritage inspections. *Int Arch Photogramm Remote Sens Spat Inf Sci* 42(2/W15):807–811. <https://doi.org/10.5194/isprs-archives-XLII-2-W15-807-2019>
- Noardo F (2022) Multisource spatial data integration for use cases applications. *Trans GIS* 26(7):2874–2913
- Oreni D, Brumana R, Della Torre S, Banfi F (2017) Survey, HBIM and conservation plan of a monumental building damaged by earthquake. *Int Arch Photogramm Remote Sens Spat Inf Sci* 42:337–342
- Pieraccini M, Miccinesi L, Abdorazzagh Nejad A, Fard NN, A. (2019) Experimental dynamic impact factor assessment of railway bridges through a radar interferometer. *Remote Sens (Basel)* 11(19):2207
- Previtali M, Brumana R, Banfi F (2020) Existing infrastructure cost effective informative modelling with multisource sensed data: TLS, MMS and photogrammetry. *Appl Geomat* 14:1–20
- Pucci A, Sousa HS, Puppio ML, Giresini L, Matos JC, Sassu M (2019) Method for sustainable large-scale bridges survey
- Purser A, Marcon Y, Dreutter S, Hoge U, Sablotny B, Hehemann L, Lemburg J, Dorschel B, Biebow H, Boetius A (2018) Ocean Floor Observation and Bathymetry System (OFOBS): a new towed camera/sonar system for deep-sea habitat surveys. *IEEE J Ocean* 44(1):87–99
- Rehman SKU, Ibrahim Z, Memon SA, Jameel M (2016) Nondestructive test methods for concrete bridges: A review. *Construct Build Mater* 107:58–86
- Riveiro B, González-Jorge H, Varela M, Jáuregui DV (2013) Validation of terrestrial laser scanning and photogrammetry techniques for the measurement of vertical underclearance and beam geometry in structural inspection of bridges. *Measurement* 46(1):784–794
- Rizzo P, Enshaiean A (2021) Challenges in bridge health monitoring: A review. *Sensors* 21(13):4336
- Salameh E, Frappart F, Almar R, Baptista P, Heygster G, Lubac B, Raucoules D, Almeida LP, Bergsma EWJ, Capo S (2019) Monitoring beach topography and nearshore bathymetry using spaceborne remote sensing: A review. *Remote Sens (Basel)* 11(19):2212
- Santarsiero G, Masi A, Picciano V, Digrisolo A (2021) The Italian guidelines on risk classification and management of bridges: applications and remarks on large scale risk assessments. *Infrastructures* 6(8). <https://doi.org/10.3390/infrastructures6080111>
- Sekiya H, Kimura K, Miki C (2016) Technique for determining bridge displacement response using MEMS accelerometers. *Sensors* 16(2):257
- Skokandić D, Vlašić A, Kušter Marić M, Srbić M, Mandić Ivanković A (2022) Seismic assessment and retrofitting of existing road bridges: state of the art review. *Materials* 15(7):2523
- Soler F, Melero FJ, Luzón MV (2017) A complete 3D information system for cultural heritage documentation. *J Cult Herit* 23:49–57
- Suhari KT, Karim H, Gunawan PH, Purwanto H (2017) Small ROV marine boat for bathymetry surveys of shallow waters-potential implementation In Malaysia. *Int Arch Photogramm Remote Sens Spat Inf Sci XLII-4/W5:42*
- Tang P, Vick S, Chen J, Paal SG (2020) Surveying, geomatics, and 3D reconstruction. In: *Infrastructure Computer Vision*. Elsevier, pp 13–64
- Terracciano DS, Bazzarello L, Caiti A, Costanzi R, Manzari V (2020) Marine robots for underwater surveillance. *Curr Robot Rep* 1(4):159–167
- Tucci G, Bonora V, Conti A, Fiorini L (2017) High-quality 3D models and their use in a cultural heritage conservation project. *Int Arch Photogramm Remote Sens Spat Inf Sci* 42:687–693
- Tuttas S, Braun A, Borrmann A, Stilla U (2016) Evaluation of acquisition strategies for image-based construction site monitoring. *ISPRS-Int Arch Photogramm Remote Sens Spat Inf Sci* 41:733–740
- Valença J, Puente I, Júlio E, González-Jorge H, Arias-Sánchez P (2017) Assessment of cracks on concrete bridges using image processing supported by laser scanning survey. *Construct Build Mater* 146:668–678
- Wetzel EM, Liu J, Sattineni TLA (2022) The use of boston dynamics SPOT in support of LiDAR scanning on active construction sites. In: 39th International Symposium on Automation and Robotics in Construction (ISARC 2022), vol 39. IAARC Publications, pp 86–92
- Wynne Z, Stratford T, Reynolds TPS (2022) Perceptions of long-term monitoring for civil and structural engineering. *Structures* 41:1616–1623
- Yu J, Yan B, Meng X, Shao X, Ye H (2016) Measurement of bridge dynamic responses using network-based real-time kinematic GNSS technique. *J Surv Eng* 142(3):4015013
- Zamboni I, Vidovic A, Strauss A, Matos J, Amado J (2017) Comparison of stochastic prediction models based on visual inspections of bridge decks. *J Civ Eng Manag* 23(5):553–561
- Zhang C, Kalasapudi VS, Tang P (2016) Rapid data quality oriented laser scan planning for dynamic construction environments. *Adv Eng Inform* 30(2):218–232
- Zheng S, Xu YJ, Cheng H, Wang B, Lu X (2018) Assessment of bridge scour in the lower, middle, and upper Yangtze River estuary with riverbed sonar profiling techniques. *Environ Monit Assess* 190(1):1–13
- Zheng S, Xu YJ, Cheng H, Wang B, Lu X, Bento AM, Gomes A, Viseu T, Couto L, Pêgo JP (2020) Assessment of bridge scour in the lower, middle, and upper Yangtze River estuary with riverbed sonar profiling techniques. *Eng Struct* 190(1):111115

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.