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A Complex Virtual Reality System for the management and visualization of bridge data

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Abstract

The management of infrastructural heritage is a central issue not only to research but also to governments wishing to conserve the state of artefacts and ensuring their safe use. The implementation of procedures for assessing the physical state of structures has increased after the recent catastrophic events causing extensive damage to national and international infrastructures. The results of the knowledge-gathering process are in the form of a quantity of data obtained using a multidisciplinary approach, and essential for defining operational procedures from a safety and conservation perspective. This paper deals with the digitization and management of heterogeneous data through Information and Communication Technologies (ICTs) to engineering and architecture with a specific focus on historical bridges. The paper discusses the results of experimentation aimed at defining an information system based on Virtual Reality (VR) for data visualization and exploitation.

Keywords

Virtual Reality (VR), Informative system, Historical bridges preservation, Data management, Interoperability, Inner Areas

1. *Introduction*

The management, sharing and use of information obtained from multidisciplinary approaches aimed at ensuring the conservation of built heritage is a central issue to academic and industrial research. These topics become particularly relevant in the analysis of certain types of artefacts, such as road infrastructure, especially if these structures are located in areas subject to other threats, such as the risk of seismic or hydro-geological events. In recent years, road infrastructures, especially bridges, have suffered extensive damages or collapse caused not only by catastrophic natural events but also lack of maintenance and overloading (EC, 2011; ASCE, 2017). A number of failures and heavy structural damages also occurred to bridges belonging to the Italian highway and road networks, which are served by structures built in the decades following World War II and currently are often more than fifty years old. As a consequence, an increased need for proper strategies for the safe management of bridges due to their nature of critical infrastructures and social and economic role pushed towards a technical and regulatory effort (MIT, 2020). As the road networks are concerned, it is worth noting that a large variety of structural solutions and materials can be found, including masonry whose age is often higher than those made of concrete and steel (Torre, 2003; Inglese & Paris, 2020). Most masonry structures are still part of the road and railway systems, especially in the Inner Areas (Barca, Casavola & Lucatelli, 2014), where they are deemed to satisfy safety requirements associated both with the routine mobility of people and goods and also with the rescue and assistance of impacted populations in the case of natural hazardous events. On the other hand, due to their age, technology and historical role in the development of settlements in Inner Areas, masonry bridges gained high historical and landmark value. Many structures, indeed, represent the architectural evidence of cultures, territories and populations turning into an essential part of National cultural heritage. Therefore, the increase of structural performance to ensure conformity to modern safety requirements must respect the basic principles for the protection and conservation of their inherent historical values. Pursuing the safety and conservation objectives of historical infrastructures represents a complex challenge, which can be achieved through an interdisciplinary effort and a holistic approach providing a comprehensive knowledge of these artefacts, as a whole and in their specificities (Lubowiecka et al., 2011; ICOMOS, 2003).

In this context, the use of digital technologies and increasingly efficient and interoperable hardware and software solutions can bring distinct advantages to the field of knowledge management, documentation and analysis of historical infrastructures. These technologies have already proved their worth in the built heritage analysis and management process by exploitating virtual representation and complex information systems. The studies carried out on the existing heritage, and a new awareness in the implementation of digital models, such as the GIS or those developed according to Building Information Modelling (BIM) processes, have highlighted that these solutions can support engineers and administrators in the collection, correlation and management of the heterogeneous data deriving from knowledge-acquirement phase (Continenza, Trizio & Rasetta, 2013; Oreni et al., 2017; Maietti et al., 2020; Bruno & De Fino, 2021).

Structural health monitoring (SHM) also represents a significant phase of these processes, particularly in the assessment of the current condition of structures (Rainieri et al., 2018). These systems enable the monitoring and control of degradation and instability, which can be triggered by catastrophic events or at any time during the life cycle of the structures. At the same time, the diagnostic and monitoring systems enable reliable assessment of expected structural performance, which in turn provides a valid support to define any interventions necessary and ensures a reduction in the time of the intervention itself.

Data processing procedures and effective data collection and management systems associated with three-dimensional models in support of the preliminary and information-analysis phases, are essential tools in the field of structural monitoring. In this context, digital models resulting from the knowledge-management process prove to be useful tools to support collaboration between different experts (Bruno & De Fino, 2021). These models can have a high level of detail and permit the collection and management of varying information in a digital environment, thus facilitating data exchange.

The natural evolution of these tools led to the development of Digital Twin (DT), a paradigm of 4.0 Industry (La Russa & Santagati, 2020) derived from the manufacturing field and applied to the architectural one. The DT represents the dynamic virtual replica of a physical system connected by a network of sensors that acquires information and analyses it in real-time, taking decisions based on simulations obtained in the virtual environment (Jouan & Hallot, 2019; Boje et al., 2020). The introduction of DT to engineering and architecture has improved the inspection and monitoring processes of built heritage (Rainieri et al., 2022), including infrastructures, and has also provided considerable advantages in the field of management and maintenance, since through the DT it is possible to intervene in a predictive manner on artefacts according to warnings given in the virtual environment.

The positive results obtained from the implementation of DT to new infrastructures (Davila Delgado et al., 2018; Ye et al., 2019; Kang, Chung & Hong, 2021) encourage the use of these systems by technical operators and decision-makers during the different phases of the infrastructural life cycle. However, the time required to implement DT may not be in line with the necessity to share information and monitor the state of health of structures to ensure their safety and conservation. Therefore, more immediate solutions based on virtual reality, have been developed to address this issue and facilitate the sharing and collaboration between the different professionals involved in the analysis and management phases.

Starting from these assumptions, several experiments on the use of VR systems for assessing the current conditions and remote inspections of built heritage have been carried out (Trizio et al., 2021a; Fabbrocino et al., 2022). The results have oriented research towards the implementation of operative procedures, multi-user and multi-level solutions able to support the gathering and management of heterogeneous data acquired at different times and with diverse levels of detail. This paper, based on gained knowledge and experience, describes a composite workflow for the implementation and validation of digital informative system based on a VR solution capable of supporting and facilitating the monitoring and maintenance of bridge stocks. Attention is focused on the procedures and the tools adopted to perform reliable analyses on the built heritage and combine and exploit their results.

The proposed methodology derives from the analysis implemented, according to a multidisciplinary approach, on the historical infrastructures located in Abruzzo, Central Italy, and in particular those along the Aterno River. The performed analyses led to the definition of an information system useful not only for operators involved in the structural health assessment but also to a wider community, including the public administrations of inner areas, which have to maintain and guarantee the use of its infrastructural heritage.

The paper is organized as follows: Section 2 deals with the research background based on the state of the art; Section 3 describes the tools selected and methodological framework for the implementation of the digital informative system; Section 4 presents the results. Finally, Section 5 and Section 6 contain concluding remarks and open issues associated with future development of the work.

2. *Research background*

The use of digital technologies in architecture and engineering has significantly changed the means of acquiring, processing and sharing of heterogeneous data provided by different specialists involved in the processes of knowledge management and analysis of the built heritage. Several studies show that it is possible to acquire valuable information about the structural state or to perform inspections of infrastructures from data gathered through various surveying procedures, and in particular from the data processing of images collected through terrestrial photogrammetry or UAV systems (Ciampa, De Vito & Pecce, 2019; Zollini et al., 2020; Pinto et al., 2020; Mishra, Lourenço & Ramana, 2022). Furthermore, these techniques provide point clouds or mesh models that can be used to develop digital replicas of the investigated artefacts and that are useful for sharing information, performing analyses and planning actions. In the context of data management and collaboration between different specialists, the benefits deriving from the implementation of informative three-dimensional models, such as parametric models, are widely recognized in scientific literature (McGuire et al., 2016; McKenna et al., 2017; Costin et al., 2018; Nili, Zahraie & Taghaddos, 2020). Indeed, digital models of artefacts can facilitate the design and construction of infrastructures and also enhance maintenance and inspection processes (Conti et al., 2022; Trizio et al., 2021b; Girardet & Boton, 2021). In addition to three-dimensional models, several experiments have been carried out to implement solutions based on virtual reality systems able to facilitate the management of and access to heterogeneous data in different formats. Among these solutions, Virtual Tours (VTs) appear to be versatile and effective tools able to become real hubs managing the multitude of information collected and meet the needs of the different users involved in the management processes (Trizio et al., 2021a). Some studies have also demonstrated the ability of this tool to respond to different technical needs, such as visual inspections or remote monitoring (Omer et al., 2019; Lasorella, Cantatore & Fatiguso, 2021; Fabbrocino et al., 2022). At the same time, other virtual or augmented reality applications have been developed to recover information and investigate structures by facilitating the process of structural monitoring and remote inspection, enabled by easier visualization and damage detection (Salamak & Januszka, 2018; Attard et al., 2018; Nguyen et al., 2018; Bacco et al., 2020; Luleci et al., 2022). In recent times more attention has been given to workflows and processes for the development of the Digital Twin (Kang, Chung & Hong, 2021; Madni, Madni & Lucero, 2019; Futai et al., 2022). This is a solution that allows implementing any physical system or object within the virtual environment, which improves maintenance and management processes and provides support to decision-makers through predictive identification of actions to be taken (Jasiulewicz-Kaczmarek, Legutko & Kluk, 2020; Mora et al., 2021).

The research performed and presented here draws on the previous experiences of the authors (Trizio et al., 2021a; Trizio et al., 2021b; Marra, Trizio & Fabbrocino, 2021; Marra et al., 2021a; Marra et al., 2021b; Fabbrocino et al., 2022). It aims to define operational procedures that can support the analysis and management processes of infrastructures, on both the territorial level and of the single object, in order to facilitate the planning of diagnostic investigations and structural monitoring using digital systems based on virtual reality (Fig. 1).

The approach adopted, in line with the recommendations shared at national and international level for risk assessment and the protection of the historical heritage (MIT, 2020; ICOMOS, 2011; ISO 13822, 2010), was multidisciplinary, in which the various sectors contributed in synergy with each other, sharing all information acquired and thereby obtaining a holistic view of the analyzed artefacts.

The analyses carried out on the historical infrastructures were performed by various experts involved in the process with a multi-scale and multi-level perspective. In this way, heterogeneous information, both qualitative and quantitative, useful for the knowledge of the artefact was acquired and then appropriately reworked and linked to the perspective of documentation and management. A geo-referenced database was defined to manage the results of the territorial analysis and to understand the spatial and typological distribution of the infrastructures, as well as their exposure to specific risk conditions (Savini et al., 2021).

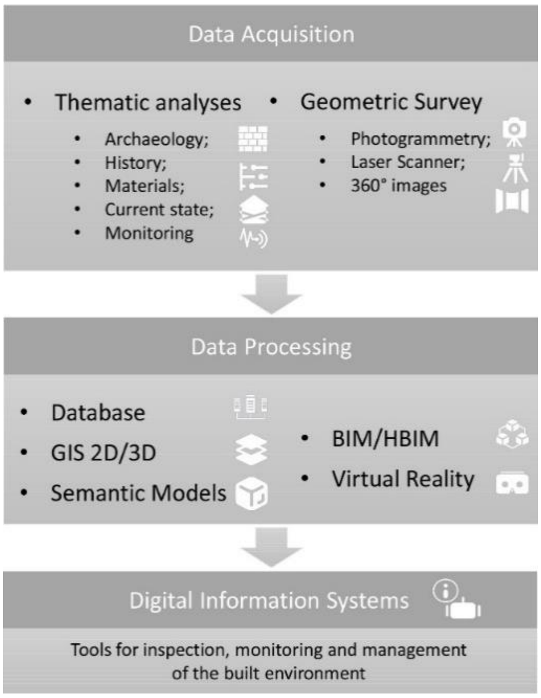

Fig. 1: General framework of the research workflow.

At the same time, geometric and dimensional data were collected on selected artefacts, using operational methods already widely consolidated for stereometric surveys. Laser scanning and photogrammetry procedures were used and integrated to obtain a reliable metric survey and high-resolution images (orthomosaics) that could support the specific analyses required. Indeed, the information derived from the morphological dimensional survey needs to be enriched and correlated with the direct observation of the artefact and with those of architectural archaeology, through which it is possible to acquire information regarding the constructive, material and typological characteristics of the artefact (Brogiolo & Cagnana, 2012; Azkarate, 2020). The correlation of this information gives an understanding of the artefact's evolution, as well as any mechanisms of damage and degradation, and contributes significantly to the assessment of the current state of the artefact and its structural performance (Savini et al., 2021; Marra, Rainieri & Fabbrocino, 2022).

However, the digitization of the structures by means of the construction of detailed geometrical models and their use in digital environments facilitates sharing and access to all collected information enhancing all aspects of inspection and planning of diagnostic and structural investigations. The experiments carried out in the context of parametric models highlight that H-BrIMs (Historical Bridge Information Modeling) are useful tools in the management and sharing of information, as well as in supporting decision-making and management processes, able to control the entire life cycle of a structure (Chong et al., 2016; Marra et al., 2021b). The creation of three-dimensional models together with the integration of the information collected and other semantic data requires considerable effort, in terms of time and resources, sometimes not repaid because they are accessible mainly to operators and specialists in the field. It is therefore necessary to use tools which can be used by authorities responsible for infrastructural heritage, such as those based on the Virtual Tour technique (Trizio et al., 2021a; Fabbrocino et al., 2022).

An additional effort was made to implement a virtual reality-based system capable of correlating the digital replica of the artefact with the information derived from the holistic approach mentioned above.

3. *Infrastructure data management in Virtual Reality*

The application of holistic methods and approaches to the analysis of the existing infrastructural heritage provides data acquisition on different temporal scales. An additional effort is therefore required in the definition of information tools and systems able to guarantee appropriate management, link the information and make it available to the people responsible for the analysis and maintenance of these works. Efforts are being made to integrate data into more or less performing digital environments and to implement digital systems that can increase, as digital twins, interoperability and make available information of the performed research to a wide range of users. In such a way, the connection and topological correlation of different data and the digital replica are guaranteed (Fig. 2).

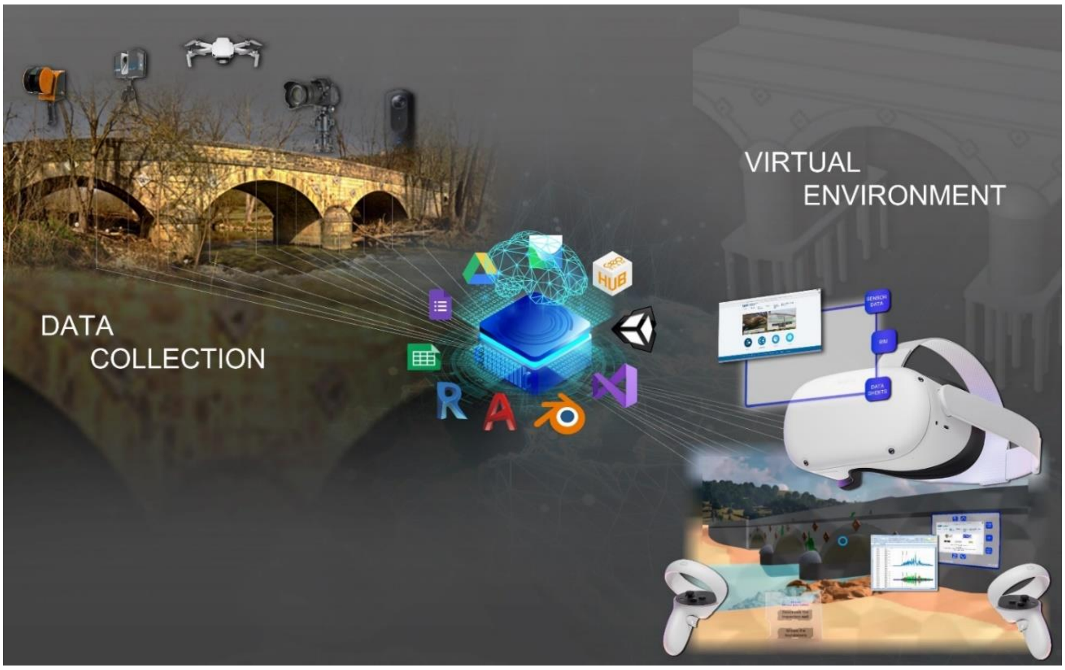

Fig. 2: Operational workflow from data collection to data elaboration and fruition in virtual environment.

Amongst the issues addressed to achieve this objective, particular importance must be given to the representation of the artefact, creating replicas as close as possible to the existing structures without losing sight of the fact that a reproduction will not fully represent the original.

The correct geometry of the copied artefact is indispensable and is the starting point for specific thematic analyses, being a representation with high precision metric standards. This is guaranteed by increasingly high-performance instrumental surveying techniques that allow for the achievement of high levels of precision in terms of both metric and color data. The use of remotely piloted instruments (UAVs) (Barrile, Bilotta & Nunnari, 2017; Roberts, Inzerillo & Di Mino, 2020) and mobile laser scanners capable of detecting moving objects thanks to SLAM technology (Simultaneous, Localization and Mapping) allows point clouds to be obtained in rapid mode and to reachinfrastructures not easily accessible. Positioning operations based on the Global Navigation Satellite System (GNSS) was used for cloud processing to obtain mesh models with photorealistic textures. This procedure ensures that the same standards are adopted in the survey of varying infrastructures, guaranteeing their connection based on geographical coordinates. The survey results therefore represent the starting point for the geometric definition of the analyzed infrastructures and facilitate the phases of creating complex digital models, as for example in the case of the creation of replicas in a BIM environment (McGuire et al., 2016; McKenna et al., 2017; Conti et al., 2022). The BrIM or HBrIM models, depending on whether the bridges is existing or new, are recognized as the principal repositories of information, including monitoring data.

The distinct advantages of the BIM process are however constrained by the difficulty of interacting with other three-dimensional data. Efforts were made to find a digital application which would combine the various formats in a single environment, to facilitate analysis and control operations of infrastructures both from the safety and conservation points of view. Virtual Reality techniques have been applied to this experimentation in order to define, starting from a Game Engine, a VR system usable both in an immersive way with performing devices and on desktop one with PC, tablet and smartphone. This application permits the visualization and integration of data resulting from the knowledge and diagnostic. The VR system for the exploitation and visualization of data in a unique environment was designed integrating open-source software for 3D modelling and management, such as the Game Engine Unity platform. The defined system, which is connected by the web to different clouds and repositories, can collect and manage multi and three-dimensional geometric data such as drawings, calculation sheets, documents and technical reports from visual inspections and diagnostic investigations. This is the starting point for the definition of a Digital Twin of the artefacts. Furthermore, the immersive VR mode developed for the Oculus Quest 2 device guarantees perception of distances and geometries, allowing an appreciation of the infrastructure in its context (Fig. 3).

Fig. 3: Free navigation test in immersive virtual reality with Oculus Quest 2.

4. The VR system for increasing, visualizing and exchanging bridge data

The dynamic design of the application by the group has led to the definition of a digital instrument capable of ranging over different scales. The starting point is the territorial scale visualising a Digital Elevation Model (DEM) photo-realistically mapped from satellite images. The DEM was obtained with the Blender open-source software using a special add-on for the management of geographical data in the modelling environment. A large portion of the territory where the infrastructures are located, which guarantee the crossing of the Aterno River in the 'Subequana' Valley area, can be displayed in the virtual world. The virtual environment has been designed as an office, or studio, with a worktable in the center upon which the DEM is placed. Thus, the user can move around the room and analyze the model from above (Fig. 4). Information on geomorphological features, seismicity and the hydrological conditions of the territory are accessible through interactive buttons allowing the consulttation of technical documentation available from the municipal and regional authorities, such as the reconstruction plans of the individual districts or the seismic activity zoning map of the Abruzzo Region (Fig. 4). It is also possible to display, on the three-dimensional map, the infrastructures in the area assessed during previous research (Savini et al., 2021), such as census sheets containing summary information on the construction work and linked directly in the virtual environment (Fig. 4). The visualization of data relating to the territorial dimension increases knowledge and understanding of the road network, and stimulate considerations on the geomorphologic characteristics and the intensity of population in the area, the layout of the infrastructures and possible alternative connection routes if the bridges cannot be accessed.

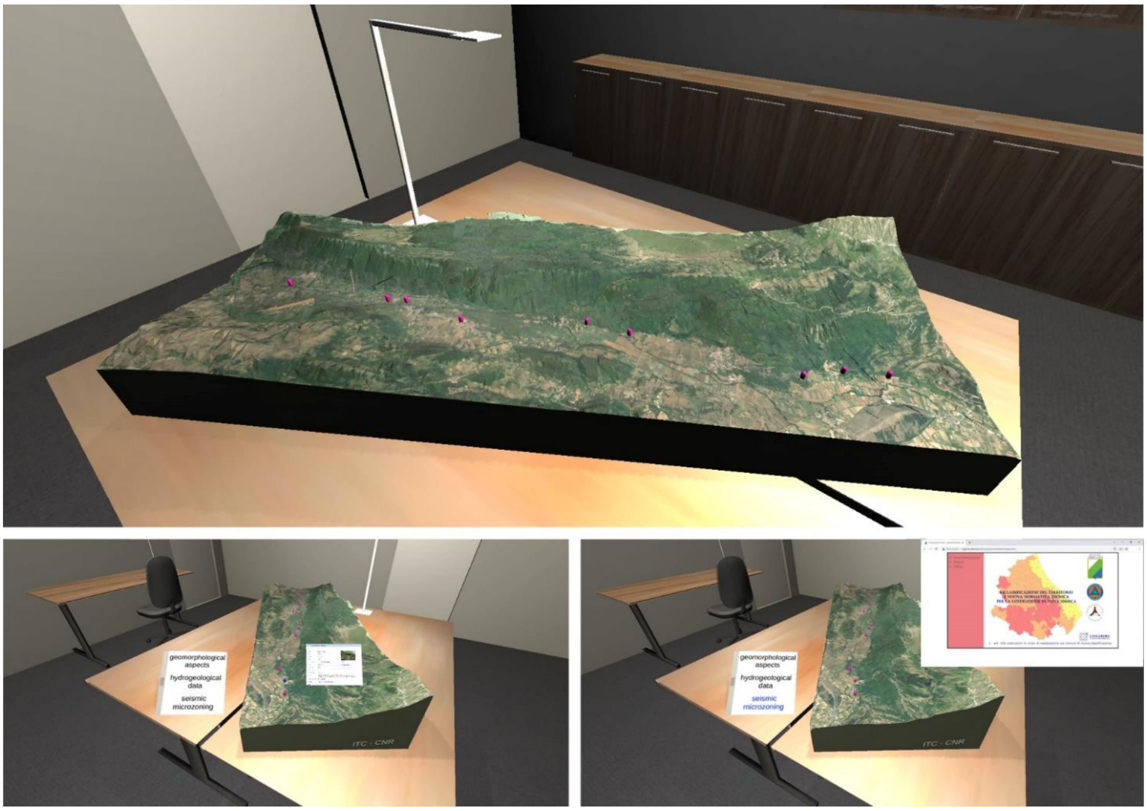

Fig. 4: The VR setting for the exploitation of territorial data: area with infrastructures on the Aterno river (top); access via data links (down).

Another advantage of the implemented VR system is its capability of switching, in the same digital environment, from the territorial to the artefact scale, and viceversa. More in detail, starting from the census sheets, it is possible, by clicking on specific hotspots on the three-dimensional map, to change the scene and navigate in person within the virtual environment, viewing the photorealistic reproduction of the selected artefact (Fig. 5). This step is facilitated by optimizing the photogrammetric model created on the basis of the integrated survey by the use of semi-automated remeshing operations to reduce the number of polygons.

The validation of this procedure for an immersive VR system was carried out on the *Ponte delle Tavole* bridge, located in the municipality of Fontecchio (AQ). The bridge is representative of a large class of structures built in local road networks of the Aterno valley, which play a relevant role in the Inner Areas. For this reason it is attractive as an explanatory case and has been analysed in the context of broad research focused on the bridges around L'Aquila. Details of the bridge are not reported herein for space constraints but can be found in Marra et al. (2021b).

The resulting light model, where the quality of photorealistic texture quality is not compromised, is easily manageable within the Game Engine and usable with medium-performance devices. The change of scale to the photorealistic model facilitates remote inspection activities to evaluate the condition and conservation of the surfaces and the presence or absence of cracks and damage. By linking to shared sheets, it is possible to complete the visual inspection forms, developed according to the Italian Guidelines (MIT, 2020), and annotate comments in real-time during the virtual visit (Fig. 6). This data will be updatable and available on different devices.

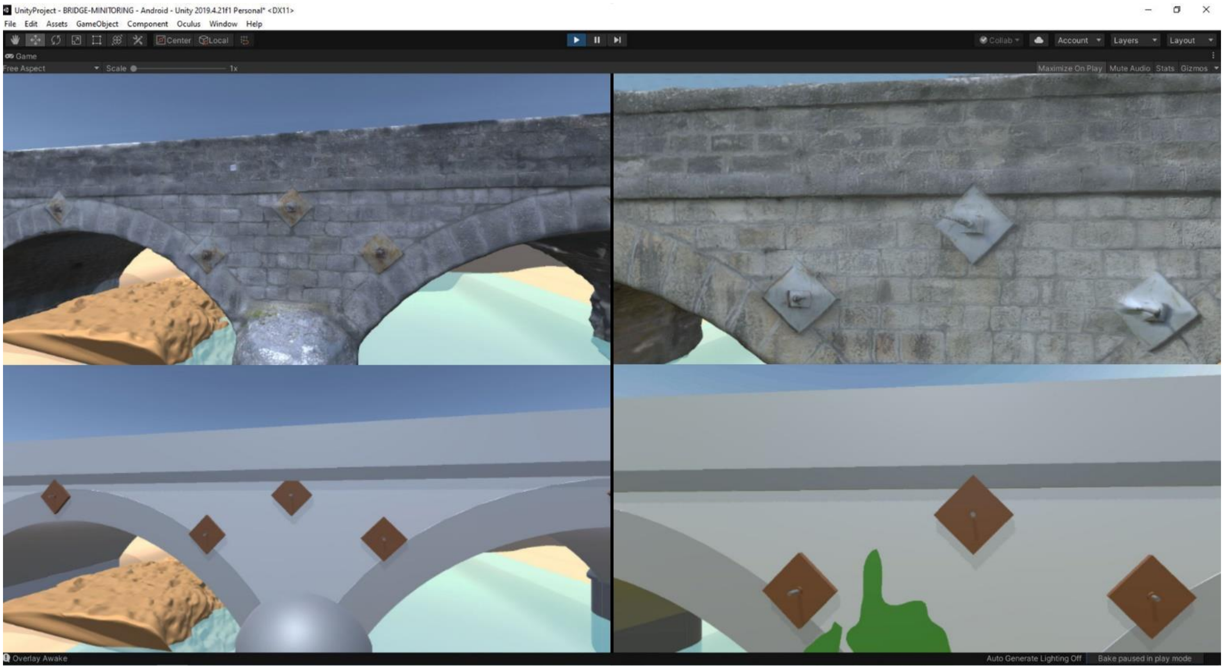

Fig. 5: Views of the design phase in the Game Engine for the switch from the photorealistic model to that derived from the BIM process.

Fig. 6: Navigation with Oculus Quest 2 of the photogrammetric model of the 'Ponte delle Tavole' bridge in Fontecchio (AQ) and the compilation phase of the visual inspection form in an immersive environment.

The VR system facilitates data validation by experts and the accessibility to information acquired over time. In particular, data collected during previous inspections (such as images, sheets and two-dimensional measurements) can be retrieved by clicking on specific buttons and activating a timeline, which is associated with photogrammetric models acquired in the past aimed at supporting and ensuring reliable and continuous monitoring of the infrastructure (Fig. 7).

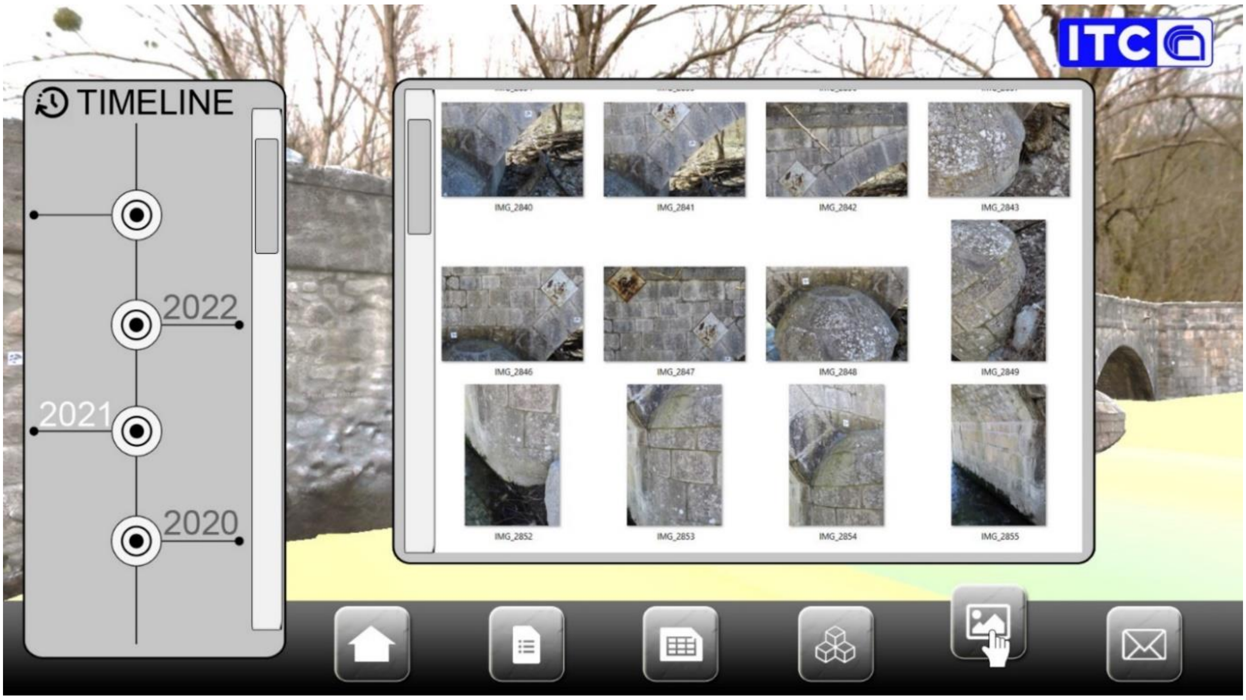

Fig. 7: Desktop view of the photogrammetric model of the 'Ponte delle Tavole' bridge with interactive buttons for accessing the data, in the example viewing the photo gallery.

The VR environment was made more realistic by enriching the surrounding landscape with spherical images acquired during the survey campaign with a 360° one-shot camera. In addition, the system can be continuously improved with data feeding into the knowledge of the artifact, such as technical reports, masonry analysis for the identification of any past modifications, material characterization and also digital representations starting with diagnostic data.

In this phase, access to the metric data is also possible by displaying the geometric and architectural surveys made at different scales, and, if available, directly the H-BrIM model of the infrastructure, thanks to the connection with the A360 platform.

Indeed, by means an authorized login of this platform, it is possible to view and enjoy the full capabilities of the parametric model making, for example, measurements in a virtual environment (Fig. 8). And even if the link to the BIM model is guaranteed by the use of this platform, the developed VR system allows the exploitation and visualization of the final product of the BIM process without use of any external link.

This was made possible by importing a threedimensional model, exported from the parametric software of the Game Engine, which allowed the transfer of the photorealistic model to the HBrIM (Fig. 9).

The modelled elements can be visualized according to the semantic division used in the parametric modelling and concerning the subdivision in structural and non-structural components and their organization in the framework of a given ontology (Marra et al., 2021b).

The three-dimensional model was linked to the data exported in CSV format by the parametric software, which can be used in the VR modality by selecting the single components described above (Fig. 10). The user can investigate the technical aspects of the infrastructure to identify the components that are not visible and understand the reasons that have affected the knowledge and modelling process.

This makes the developed tool also suitable for technical considerations and observations.

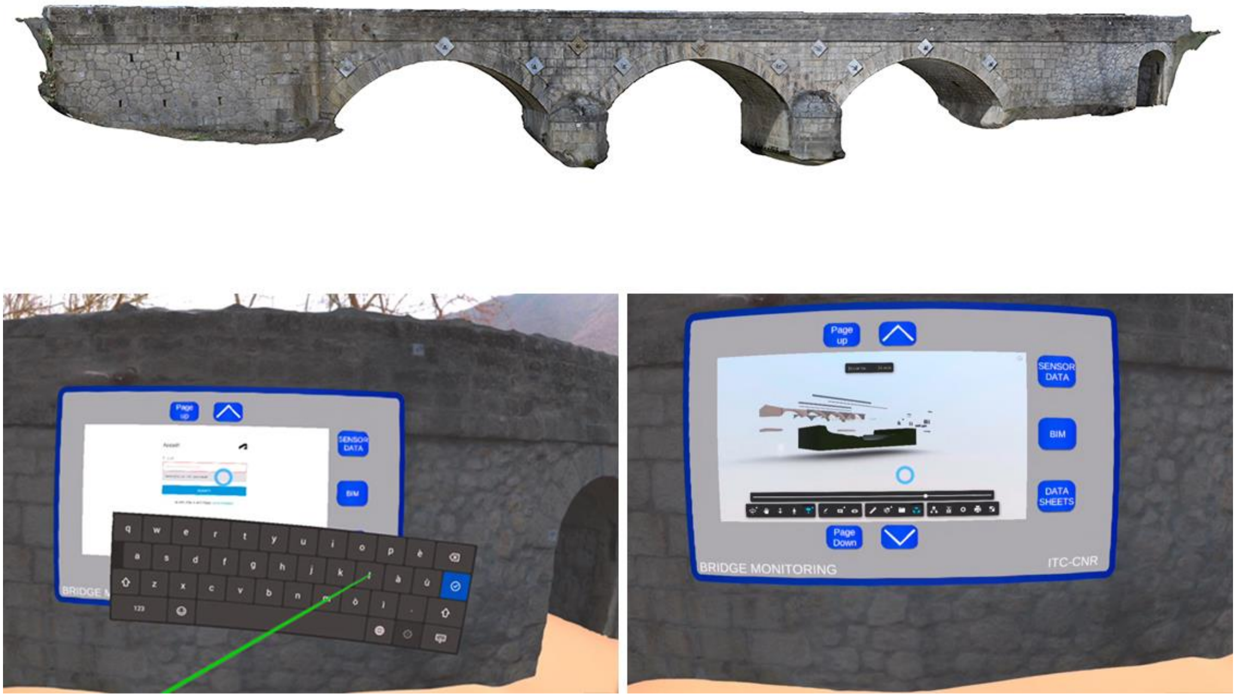

Fig. 8: The photogrammetric model of the bridge (top). Visualization and query in the immersive VR environment of the BIM model, accessible via link to a single repository after login (down).

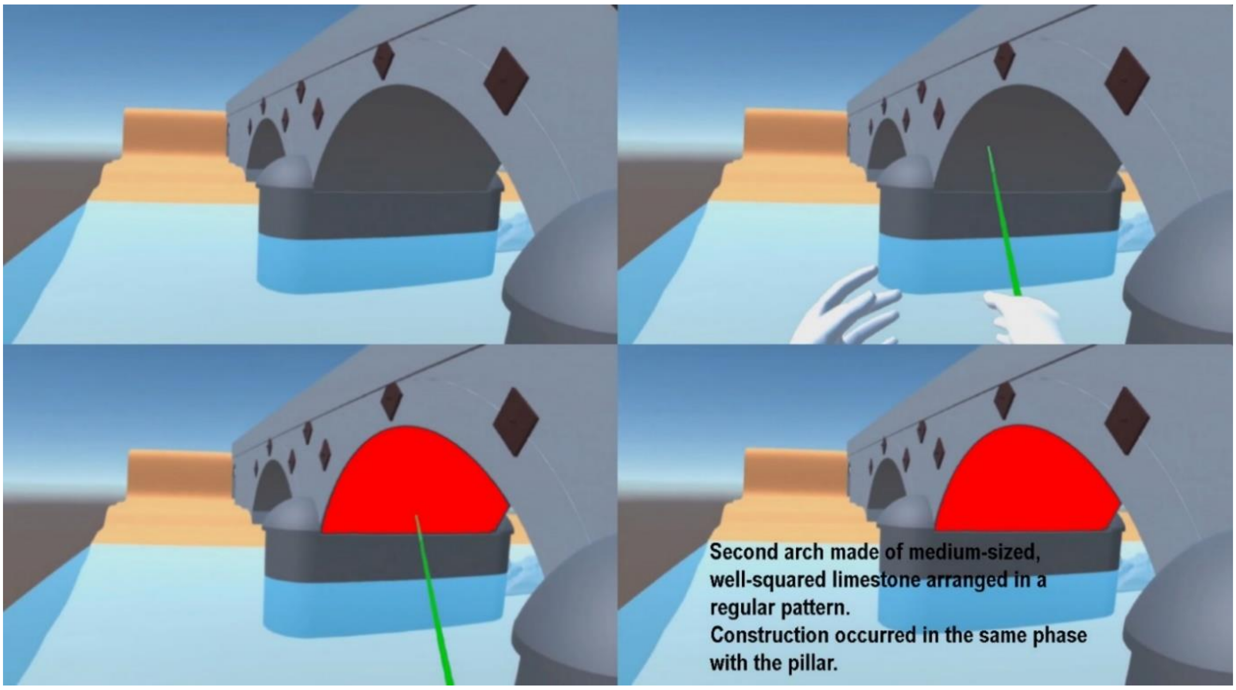

Fig. 9: Navigation with Oculus Quest 2 of the 3D model resulting from the BIM process of the 'Ponte delle Tavole' bridge. The VR system allows the query of the single components that make up the structure, ensuring access to the data.

One example is the foundations of pillars on piles, modelled from data in the manual (Torre, 2003), or the core of the bridge that constituted the filling of the vaults, modelled from the results of comparative analyses with similar structures for which it was possible to analyze the interior (Fig. 11).

The model also makes visible data regarding the state of conservation thanks to the three-dimensional representation of the extent and form of degradation to which are linked specific information about the entity and any interventions to be carried out (Fig. 11).

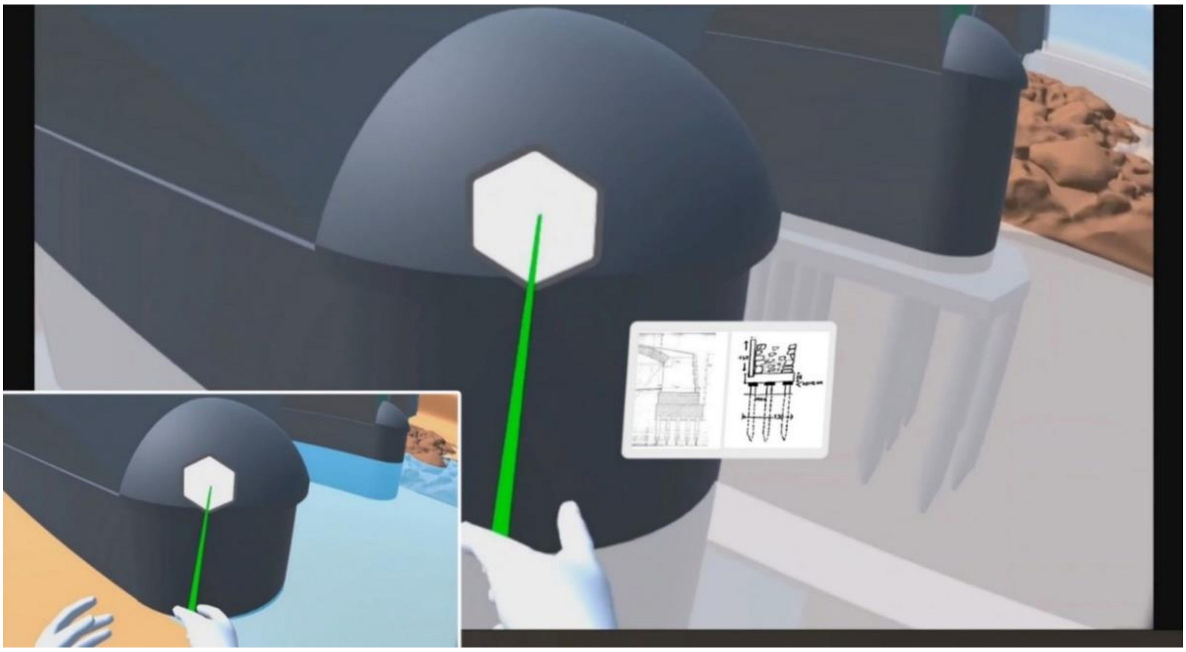

Fig. 10: VR visualization of non-visible bridge components and related information that clarifies the modelling process.

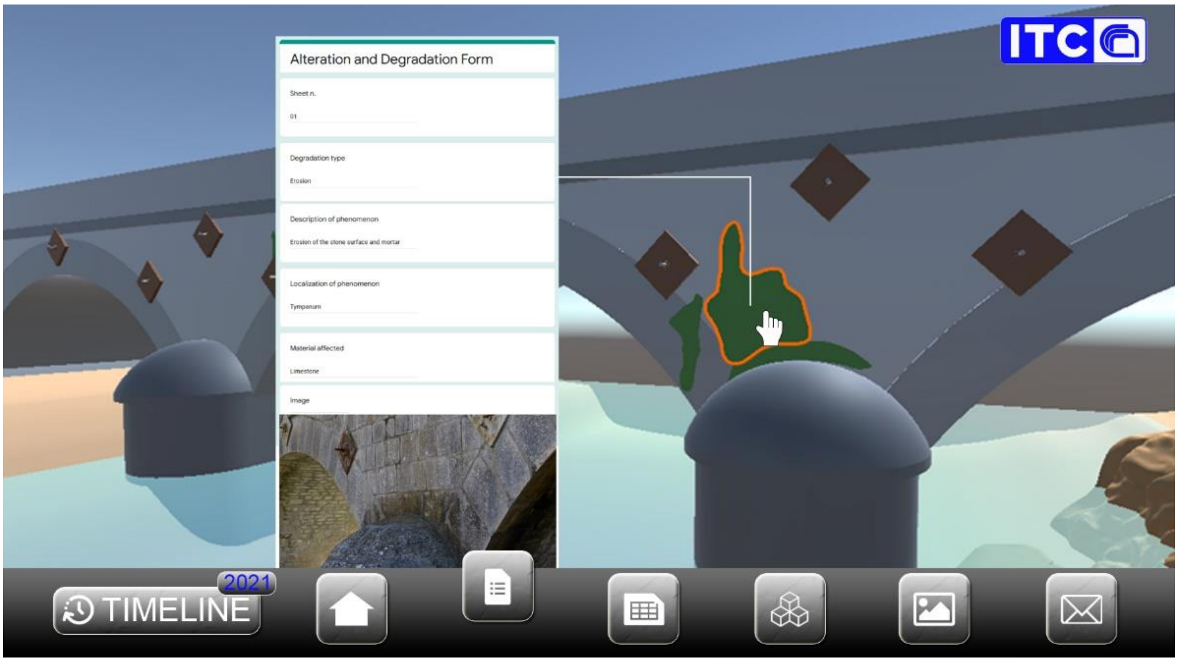

Fig. 11: The three-dimensional model of the 'Ponte delle Tavole' bridge in desktop mode with interactive buttons to access the data, in the example visualization of Alteration and Degradation shaping.

These data refer to the defect detected (*Defect*) and its extension and intensity coefficients (*K1-Extent* and *K2-Intensity*), as already tested for the degradations modelled in the parametric environment (Trizio et al., 2021b). A weight (*G-Defect weight*), according to the Guidelines, was assigned for each defect to estimate the Relative and Absolute Defect Index (*DR - Relative Defect Index* and

DA - Absolute Defect Index), as required by the first-level assessment defined by the same regulations.

Finally, a link was created to the data acquired through a Structural Health Monitoring system to display indicators and results that ensure maintaining the safety of infrastructure assets. Data from accelerometers referred to the three directions and were acquired during monitoring campaigns; these data showthe presence of moderate peaks due to the passage of vehicles. These processed data are visible in the VR system thanks to a link created to the digital representation of a virtual accelerometer modelled in a parametric environment. The sensor's replica also provides the access to a datasheet, which favors the use of the information in an inclusive way, and able to make a comparison of results with those derived from the multidisciplinary analyses of the infrastructure (Fig. 12). The data collected by the surveys, which can be implemented, updated and remotely verified in the VR environment, facilitate the assessment of risks to which the infrastructures are exposed and, consequently, the definition of the "Classes of Attention" (CoA) required by the Guidelines in level 2 of the regulations (Santarsiero et al., 2021). The designed VR can therefore be considered an effective tool for the planning of maintenance and safety actions necessary to ensure the preservation of historical infrastructures.

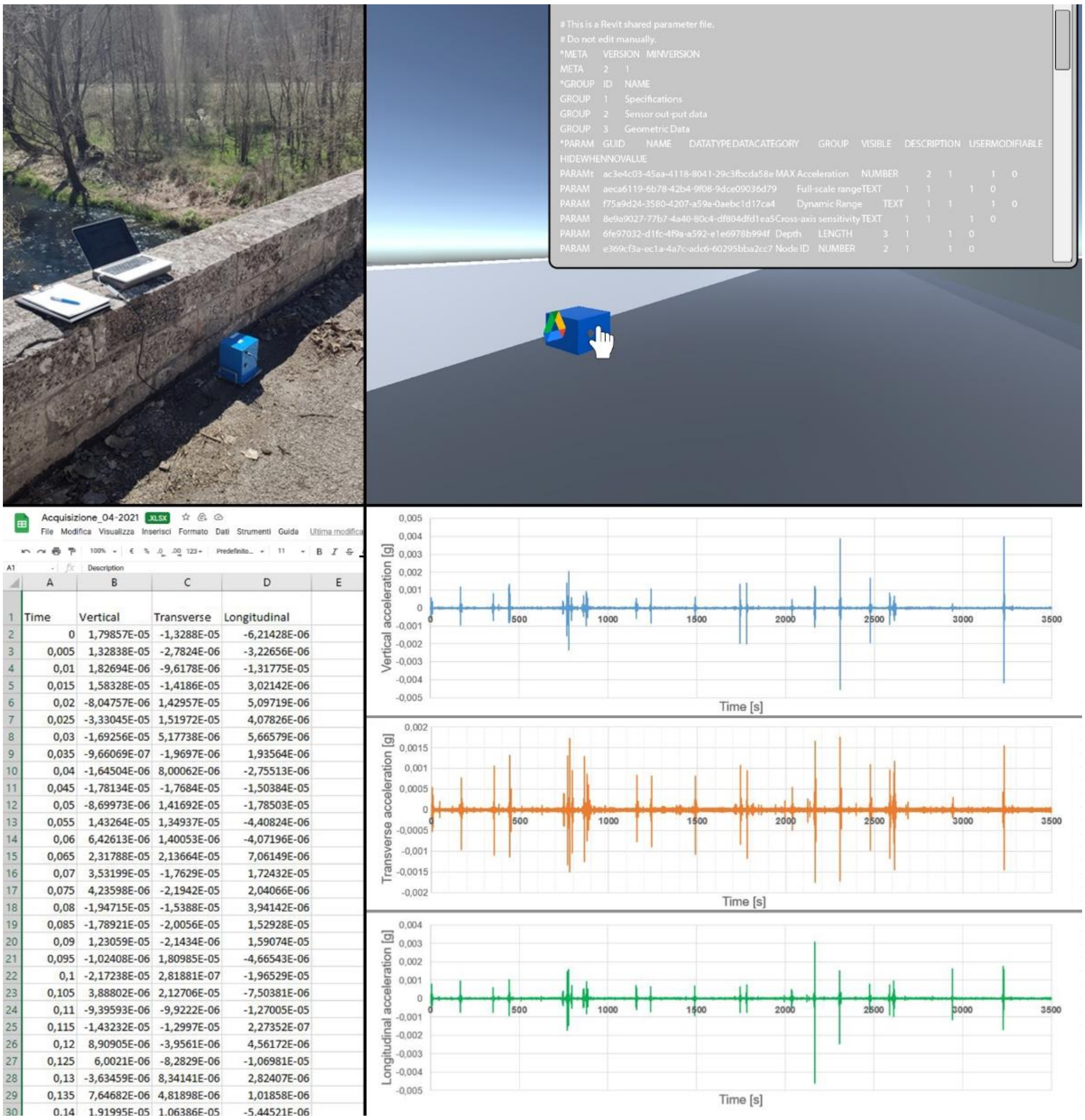

Fig. 12: Virtual model of the sensor with access to modelled parametric sensor data and link to stored accelerometric data

5. Discussion

The procedure implemented and illustrated in this paper has led to the development of a Virtual Reality Informative System that integrates multi-data and facilitates interoperability between the different actors involved in the processes of knowledge, conservation and management. The strength of the system, usable in different ways, is in the availability and real-time exchange of multiple information, directly linked to a digital representation which is navigable in a virtual environment. The system was developed exploiting the advances achieved in recent years in ICT, and specifically in the fields of engineering and architecture. The results demonstrate the effectiveness of digitizing complex processes relating to the maintenance and safety of historic infrastructures. Indeed, the application has several advantages in ordinary inspections and supports the assessment of the current condition of existing infrastructures. The availability of instrumental monitoring data, correlated with multiple contextual and historical information, provides a holistic view of the artefact, becoming a useful tool for public administrations. The accessibility of such data, favored by VR in desktop mode, becomes a new strength since it increases digital tools used in the perspective of e-conservation (Marra et al., 2021b; Trizio et al., 2021b). According to the e-government paradigm, namely the increasing use of digital solutions in the Public Authorities (PA) to facilitate the management of services to the citizen, innovative systems are being developed to provide municipalities with digital tools that increase their knowledge of the existing heritage and improve decision-making processes for its conservation. This becomes more relevant when addressed to small administrations located in the inner areas of Italy, which, unlike large infrastructure operators, are often faced with constraints in terms of personnel and resources and therefore unable to offer training on digital issues.

Furthermore, historical infrastructures are spread all over the territory within the inner areas, which is often characterized by narrow valleys crossed by rivers. These artefacts have to be maintained to ensure the safety of the structures themselves and eliminate the risk to human life since they are often subject to external stresses linked to multiple causes, both natural and man-made. Beyond the safety issues, these infrastructures are in the main all crucial parts of the road network because they guarantee the operability of obligatory routes also providing access to settlements. The instrument developed, easily accessible thanks to the desktop mode, the use of online repositories and for its user-friendly interface not requiring special skills, therefore becomes functional for the management of historical bridges by public administrations whilst not overlapping with the popular Bridge Management System (BMS), platforms developed at regional or national level (AINOP; ARGO; Manarin et al., 2022).

Although the results are encouraging, the research is already being directed towards the improvement of the VR system, aiming for its use as a tool for planning instrumental monitoring since it offers the possibility to evaluate where to locate sensors and methods for SHM data acquisition.

Furthermore, work is being carried out to implement novel approaches to the exploitation of on-site data based on Augmented Reality. In this perspective, an operational procedure to visualize data resulting from later analyses and visual inspections by overlapping them with the real object is being defined by using mobile devices and more powerful tools such as HoloLens (Nguyen et al., 2020; Mascareñas et al., 2021). This development will improve the monitoring of infrastructures over time, allowing the assessment of damage evolution to ensure the proper conservation and safety of artefacts.

Digital replicas of real artefacts, both photorealistic and those developed from more or less complex modelling processes, correlated with information from static structural monitoring, currently represent the starting point for the development of Digital Twins. The evolution of Machine Learning and Deep Learning techniques in the perspective of artificial intelligence leads to orienting future research towards the automated acquisition of data (Garozzo, 2021) and make it easily repeatable over a long period, as well as the real-time acquisition of monitoring data thanks to the strengthening of broadband and the development of 5G technology. The correlation in a virtual environment of more data, not only those presented here but also those derived from dynamic monitoring repeated over time and useful for creating simulation models, will favor processes aimed at territorial development and, above all, safety, not only that of infrastructure but also to human lives.

6. Conclusion

The paper reports the main outcome of research aimed at investigating the opportunities offered by current technologies in the integration of inspection and structural health monitoring data by using digital platforms based on advanced digital survey and representation techniques. Attention is particularly focused on masonry bridges still operational in many areas and in particular those located in the so-called Inner Areas. The results show encouraging perspectives of application in managing existing infrastructure by means of the design of optimized and comprehensive information systems exploiting Virtual Reality. It has been tested and validated the capacity of facilitating in situ visual inspections for assessing the state of conservation and the accessibility to data, especially photorealistic overlaid on alphanumeric data.

The advantage of the tool is that it is functional not only in visual inspection operations but also in the management of infrastructures since the informative system created facilitates the decision-making work of stakeholders responsible for guaranteeing the conservation and safety of infrastructures. Besides the strengths described in this paper, some critical points were also highlighted in the definition phase of the VR information system that indicated testing towards different solutions. In particular, the problems related to the device for virtual reality, both in terms of availability since not all PAs have funds and specialized staff able to make use of such systems and operator resistance to the 360° virtual environment, contribute to these issues. A desktop application for PCs to deal with such evidence was created, which proved to be very powerful in making such multi-data available to a wide target and users, thanks to its user-friendly interface. Finally, the commonly used online tools and repositories become a further strong point that increases the accessibility of data by PAs in the VR Informative System since it does not require particular computing power or specific machine features.

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Credits

The research presented is the result of the authors' collective work, of continuous comparison and of a common discussion. Francesca Savini wrote sections 3, 4 and 5. Adriana Marra wrote sections 1 and 2. Alessio Cordisco implemented the VR system. Marco Giallonardo realized the integrated digital survey. Giovanni Fabbrocino and Ilaria Trizio supervised the research, reviewed the work and wrote section 6.

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