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Estimation and Integration of 3D PS-InSAR Data for Enhanced Structural Health Interpretation using BIM-Based Models

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ABSTRACT

The growing need for advanced research in the proactive management of civil engineering works has sparked increasing interest in the integration of geospatial technologies, information modeling, and virtual environments. In this context, satellite radar interferometry (InSAR) has proven to be a reliable tool for multi-temporal surface displacement monitoring, which can then be used to infer patterns which can subsequently be analyzed to infer patterns of structural or ground deformation. However, the interpretability of InSAR processing is often hindered by two primary challenges: the spatial and directional relativity of the measurements, which are confined to the satellite's line-of-sight and are relative to a user-defined reference point; and the difficulty in precisely geolocating persistent scatterer (PS) points and semantically linking them to specific structural elements, a limitation that stems from undetermined geolocation precision and the lack of inherent contextual information in the InSAR data itself.

This research introduces an integrated methodological approach combining high-resolution satellite InSAR observations, georeferenced Building Information Models (BIM) to enhance both spatial and semantic accuracy in PS analysis. A key element is the structured data integration between heterogeneous sources such as satellite observations, geospatial coordinates, and BIM geometry, enabled by the geodetic alignment of InSAR data with absolute terrestrial reference systems and the projection of PS within the BIM environment. This process enables more reliable association of PS with discrete construction elements.

This semantic mapping, combined with three-dimensional representation, allows for a more comprehensive interpretation of detected displacements, supporting the identification of potential issues not directly linked to structural failures. The resultant BIM serves as the connection between infrastructure elements and the processed InSAR displacement estimates, thus improving the reliability of the analysis as well as promoting a push towards operational deployment for a Digital Twin system.

The application in case studies demonstrates the potential of the dynamic and multimodal Digital Twin paradigm as an operational tool for decision support, predictive maintenance, and infrastructure resilience.

Keywords: Infrastructure monitoring, InSAR, Digital Twin, Building Information Modeling (BIM), remote sensing, geospatial data integration, deformation analysis, predictive maintenance

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1. INTRODUCTION

Nowadays, remote sensing technologies have gained remarkable relevance in the monitoring of civil infrastructures, offering innovative tools to complement traditional inspection and sensing approaches [1,2].

The rapid development of new satellite constellations, as well as advances in spatial resolution, shorter revisit times, and new image processing methods, has extended the use of Interferometry of Synthetic Aperture Radar (InSAR)-based methods from monitoring of displacements at regional scales to the observation of localized deformations in the built environment. In optimal conditions, these methods enable the measurement of displacements with millimetric accuracy on large areas without any ground-based monitoring. Satellite radar monitoring is therefore suggested as a powerful approach supporting large-scale and long-term analysis of infrastructures [2].

Satellite remote sensing, and more specifically through InSAR, has emerged as one of the most promising approaches for continuously monitoring civil infrastructures. Through the analysis of the phase difference between consecutive radar acquisitions, InSAR allows to quantify surface displacements on a millimetric scale on large areas and longtime spans. Innovation in multi-temporal methods like Persistent Scatterer Interferometry (PS-InSAR) has boosted even more this technique's capabilities, by enabling the reconstruction of time series of displacements for targets that exhibit stable scattering behavior and can be consistently identified as persistent scatterers in the radar images. Present applications of PS-InSAR include a huge number of subject matters, such as subsidence monitoring over large areas, landslides, earthquakes' displacement monitoring, and local settlement detection in engineering structures.

For practical applications, satellite-measured scatterers must be reliably linked to structural assets of engineering interest; this requires moving beyond generic ground displacement maps and achieving a clear identification between radar observations and specific structural elements

Although PS-InSAR has been successfully applied to detect deformation patterns at both regional and urban scales, its interpretation in the context of infrastructure monitoring remains challenging. A key limitation lies in ensuring that the measured displacements can be confidently associated with specific structural elements.

A fundamental limitation concerns spatial accuracy in PS location. Although displacement velocities can be measured at millimetric accuracy, the precise geolocation of scatterers is subject to variable and sometimes substantial uncertainty. This uncertainty depends on several factors, including radar imaging geometry and processing assumptions, and is rarely quantified or explicitly considered when associating InSAR measurements with physical structures. This asymmetry arises both from intrinsic properties of radar imaging geometry and simplifications implicit in processing. Therefore, the deformation signal sensed by a PS cannot typically be attributed to an identifiable structural element. A subsiding scatterer near a bridge, for example, could be related to a pier, on the deck, or could be any part of the nearby terrain. This ambiguity fundamentally limits the capability of PS-InSAR to aid engineering decisions, where accurate attribution of deformation to structural elements is critical.

Some efforts have been spent to overcome these constraints by integrating InSAR measurements with complementary data sets, such as airborne LiDAR point clouds, which can be used to refine the geolocation of Persistent Scatterers [3]. By connecting radar points to high-density 3D geometries, it is then feasible to better position them in space and to better attribute deformation signals to physical features at the building scale. This represented an important step towards a realistic interpretation of InSAR measurements, showing interesting approaches regarding the combination of radar measurements and external 3D sources. However, merging InSAR data with point clouds obtained from laser scanning technologies doesn't add any semantic information regarding the infrastructure, rather it only provides geometric enrichment, improving positional accuracy. In fact, a point cloud is a group of coordinates with no inherent knowledge about structural roles or attributes of the elements it represents and therefore does not present much usefulness for structural diagnosis on its own. Later research has considered the problem of precisely defining the location of scatterers in signal processing terms. It is generally true that the effective phase center of a scatterer will not coincide with the nominal location of a pixel, leading to homogeneous sub-pixel errors [4]. Also, the ubiquity in urban regions of a high density of scattering phenomena, such as double and triple-bounce reflections, makes the assignment of PS to recognizable physical objects even harder.

Even using advanced correction methods such as sub-pixel shifting, corner reflectors, or support from digital terrain models will tend to leave localization errors of a PS subject to meter-level biases. This uncertainty makes it difficult to establish a

reliable correspondence between observed displacements and specific structural elements; more important than reducing the uncertainty itself is to accurately estimate and explicitly account for it when interpreting scatterers.

These constraints indicate the persistence of an imbalance; while PS-InSAR provides accurate deformation measurements, translation into operational Structural Health Monitoring (SHM) systems requires a more explicit and formal relationship between PSs and the built environment. Aiming at the full exploitation of satellite radar monitoring's potential, there is a need to go beyond simple geometrical integration and adopt solutions that place deformation data in the context of semantically qualified infrastructure models [5].

Building Information Modeling (BIM) offers such a possibility, providing parametric representations of construction components enriched with attributes, classifications, and hierarchical relationships [6,7]. By projecting PS-InSAR data into BIM environments, it becomes possible to anchor satellite observations to structural elements such as piers, arches, and decks, thereby enabling a more meaningful interpretation of displacements.

2. AIMS AND OBJECTIVES

This study proposes a methodological framework that combines satellite-based observations with BIM. The main aim of this paper is to advance the use of Persistent Scatterer Interferometry as a tool to support the structural assessment of critical assets, by overcoming current limitations in the localization and interpretability of scatterers.

Within this framework, the research investigates the integration of high-resolution multi-temporal SAR constellation data, such as COSMO-SkyMed, within BIM environments. An objective is to find the best process to link persistent scatterers into BIM-based models through accurate georeferencing procedures, thereby enabling a direct and reliable correlation between PS measurements and individual construction elements. By embedding deformation data within object-oriented models, the study aims to move beyond purely geometric representations and towards a structured, component-level understanding of infrastructure response.

3. METHODOLOGY

3.1 Data sources

The methodological workflow (Fig.1) developed in this study is based on two complementary data sources: (i) a dataset of Persistent Scatterers derived from COSMO-SkyMed acquisitions, and (ii) a BIM model generated from a georeferenced point cloud survey of the bridge.

The interferometric input is provided as the final output of a PS-InSAR processing procedure applied to data provided by the COSMO-SkyMed mission. The data are delivered in CSV format and contain, for each persistent scatterer, different attributes, such as geographic and projected coordinates, altitude information, quality parameters (e.g., coherence, precision), and deformation attributes. These deformation data include average velocity, cumulative displacement, and multi-temporal displacement values for 20 SAR imageries selected between December 2020 and October 2022.

The tabular structure facilitates the selection and filtering of PS associated exclusively with the selected infrastructure. By constraining the dataset to the spatial extent of the bridge under analysis, only relevant PS are retained and subsequently linked to the different elements of BIM model. Furthermore, by applying displacement rates, it is possible to highlight scatterers affected by significant displacements, thereby supporting the identification of possible localized anomalies such as subsidence phenomena or deformation trends potentially critical for the infrastructure asset.

The BIM model of the infrastructure is obtained from a georeferenced 3D point cloud survey, acquired through reality-capture techniques such as terrestrial laser scanning and UAV photogrammetry. The survey is registered in a geodetic reference system to ensure compatibility with external geospatial datasets. The point cloud is then processed within a BIM environment, where structural components are modeled as parametric 3D element (e.g., piers, decks, arches, abutments). This approach guarantees that the digital model not only reproduces the geometry of the asset but also incorporates semantic information, enabling subsequent enrichment with external data sources.

The combination of a PS-InSAR datasets and a georeferenced BIM model generated from point cloud data forms the initial step of the proposed methodology. Within this framework, satellite-derived displacement can be linked into the BIM environment and associated with construction elements in a parametric and coherent way.

3.2 Data integration workflow

The integration workflow developed in this study provides a structured procedure to incorporate PS into a digital model. The approach ensures that PS data, originally available as tabular outputs of interferometric processing, are not treated as abstract points but as data-rich entities directly linked to the structural components of interest.

The workflow begins with the import of the PS-InSAR dataset, delivered as a CSV file containing coordinates and deformation attributes for each PS. This structure provides an effective basis for integration, as it allows PS to be directly linked within a digital modeling environment.

Once imported, the dataset undergoes a georeferencing and coordinate alignment step. The positional values contained in the CSV are expressed in geographic and projected coordinates that must be transformed to align with the reference system adopted by the BIM model. This ensures spatial consistency between the satellite observations and the digital reconstruction of the infrastructure, making it possible to superimpose PS data on the structural geometry with sufficient accuracy to allow engineering interpretation.

The aligned dataset is then used for the representation of PSs in the three-dimensional BIM environment, allowing the association of each one to a specific asset of the analyzed structure. Furthermore, parametric BIM elements are created to serve as placeholders for each PS, allowing their visualization in the digital environment. These are typically represented as three-dimensional spheres, which are instantiated at the georeferenced coordinates derived from the PS catalog. The result is a BIM model that not only contains the surveyed asset geometry but also hosts a distributed set of points corresponding to persistent scatterers derived from satellite monitoring.

The following phase of the process consists in the integration of attributes to the digitized PSs. Non-spatial parameters from the CSV file, such as displacement velocity, cumulative displacement, coherence, and time-series observations, are imported and associated with the BIM elements created for each PS. This step enriches the BIM model with analytical content: each PS is no longer just a geometric point, but an informative object containing deformation metrics that can be queried and analyzed within the model.

The enriched PS are subsequently linked to structural components in a semantic mapping step. Through spatial proximity and parametric association, scatterers are assigned to discrete construction elements such as piers, arches, decks, or abutments. This transition from geometric points to semantically mapped data creates an explicit bridge between remote sensing observations and structural elements, thus enhancing the interpretability of deformation measurements. Instead of remaining abstract indicators, PSs become structural attributes that reflect the behavior of specific parts of the infrastructure.

Finally, the workflow incorporates a stage of data analysis and thematic representation. Deformation attributes, particularly velocity values, are processed to produce thematic visualizations within the BIM environment. A graduated color scale is applied to represent different deformation rates, making it possible to rapidly identify anomalous points or localized patterns of movement. Beyond visualization, this stage enables the data to be interpreted, as scatterers can be filtered by coherence or velocity thresholds, grouped according to their association with structural components, and analyzed in relation to the overall geometry of the bridge. In this way, the BIM environment becomes the key element integrating and interpreting satellite-derived measurements in a structural health monitoring context.

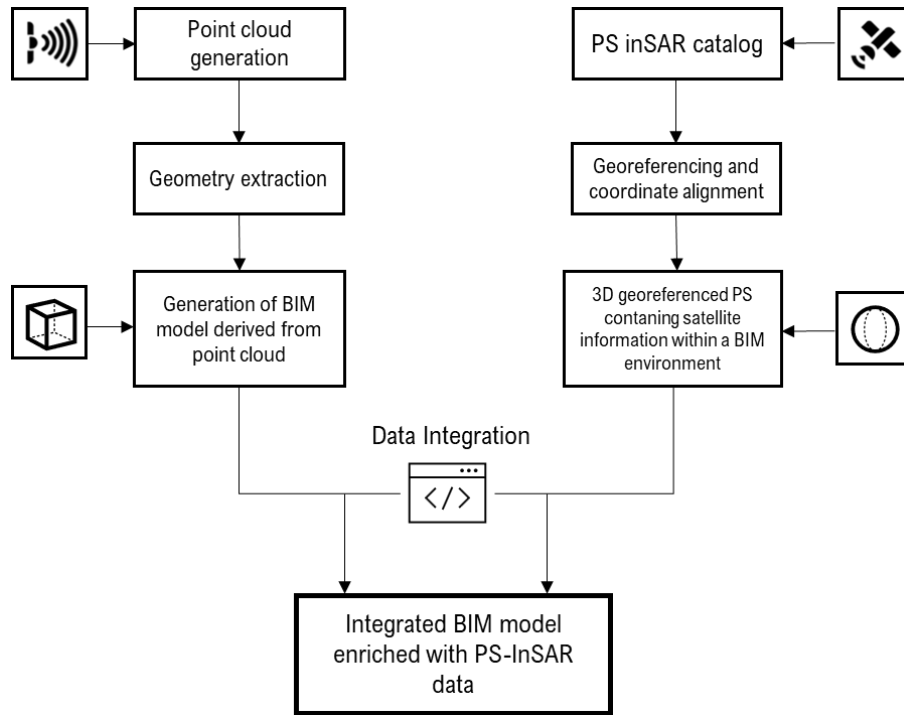


Fig.1 Proposed methodology

4. CASE STUDY

The selected case study is a masonry arch bridge in the Lazio region, Italy. The geometric reconstruction of the bridge was derived from a georeferenced point cloud acquired through laser scanner and drone data. The dataset was registered to an absolute geodetic reference system, ensuring consistency with the satellite-derived PS dataset.



Fig.2 Point clouds of the inspected infrastructure

The point cloud was subsequently processed to generate a BIM model in which the main structural elements were reconstructed as parametric objects.

The BIM model includes key components such as piers, spandrel arches, deck, and abutments, each represented as an informative element enriched with attributes. This structuring enables the model to serve not only as a faithful geometric

replica of the bridge but also as a semantic environment into which external data sources can be embedded. In this context, the BIM model represents the digital basis of the proposed approach, providing the reference system for the integration of PS-InSAR observations and the resulting association of the deformation data with discrete structural elements. (Fig.3).

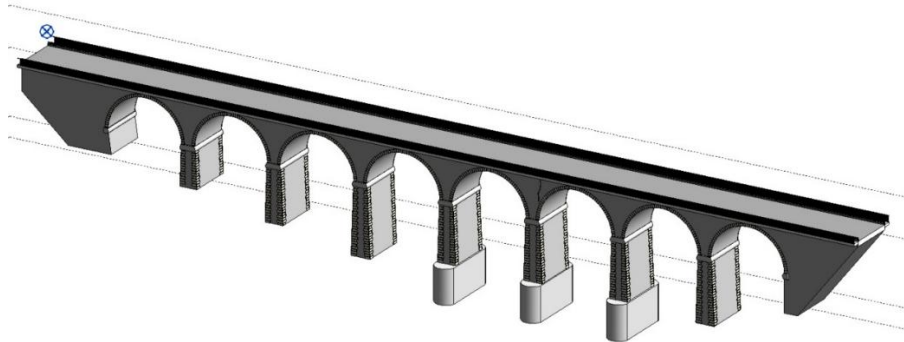


Fig.3 BIM model reconstruction of the inspected infrastructure

The satellite dataset used in this study consists of the output of a PS-InSAR analysis obtained from COSMO-SkyMed acquisitions. The results were provided in tabular format (CSV), containing positional information, quality descriptors, and displacement measurements for each scatterer. The catalog comprises a total of 213 persistent scatterers, spanning an observation period from December 2020 to October 2022, with approximately 20 dates.

The integration of PS-InSAR data into the BIM environment is carried out following the workflow described in the previous section 3.2, with the aim of transforming satellite-derived measurements into semantically meaningful information associated with the structural components of the bridge.

The geographic coordinates contained in the PS catalog are first transformed into their corresponding ones related to the geodetic reference system adopted by the BIM model, ensuring spatial consistency between the scatterers and the geometry reconstructed from the point cloud survey. Each persistent scatterer is then instantiated in Autodesk Revit using adaptive components defined as simple parametric objects (e.g., 3D spheres), which are positioned at their respective coordinates. This procedure enables the direct embedding of scatterers into the three-dimensional model of the bridge.

To enrich these geometric placeholders with analytical content, the deformation attributes included in the dataset, such as average velocity, cumulative displacement, coherence, and multi-temporal observations, are imported from the CSV and assigned to the parametric families. In this way, each PS becomes a data-rich object containing both spatial positioning and deformation metrics.

A semantic process is subsequently applied, whereby scatterers are linked to the closest structural elements, such as piers, arches, the deck, or abutments. This step is fundamental to shift from a purely geometric alignment to a structured representation in which displacement values are explicitly associated with construction components.

To streamline and automate this workflow, a custom algorithm is implemented in Dynamo, which is the visual programming environment embedded in Autodesk Revit, with additional modules developed in Python. The script is designed to import the CSV file, read positional and analytical attributes, generate adaptive elements at the correct coordinates, and assign the deformation values as parameters of each scatterer. Furthermore, the script applies thematic classification rules, such as color coding based on velocity ranges, thereby producing an immediate analytical representation of the dataset within the BIM environment. The logic of the algorithm can be summarized in five main steps:

1. *CSV import*: reading positional and analytical information for each PS.
2. *Coordinate transformation*: adapting geographic and projected coordinates to the BIM reference system.
3. *Adaptive components*: creating 3D markers at the positions of PS.
4. *Attribute assignment*: linking deformation parameters (velocity, cumulative displacement, coherence, time-series) to each family.

5. *Thematic classification*: applying color schemes to visualize deformation patterns according to analytical thresholds.

This automated approach significantly reduces the time required to integrate PS dataset, minimizing manual errors and ensuring reproducibility. Moreover, the modularity of the script makes it adaptable to other datasets or infrastructure typologies, providing a scalable tool for future applications. The workflow implemented is illustrated in Fig.4, which shows the script developed for the case study, highlighting the different steps previously described.

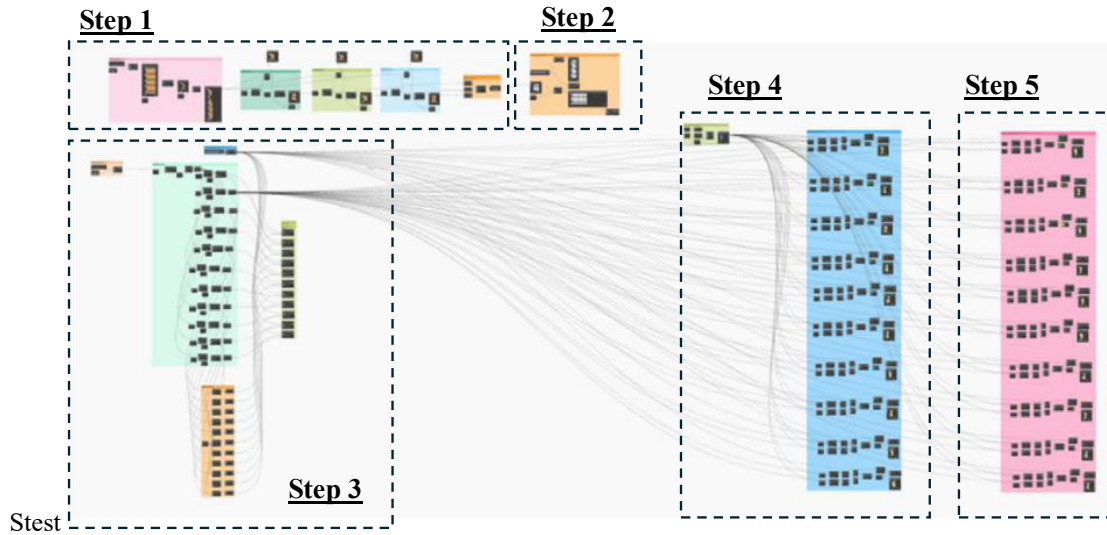


Fig.4 Overview of the developed algorithm

The outcome of the integration process is a dynamic digital model in which persistent scatterers are directly linked to the structural components of the bridge. Within this enriched environment, the satellite-derived observations are no longer isolated points but are visualized in a realistic and immersive context, enabling their interpretation in relation to the geometry and semantics of the structure (Fig.5). Such a representation enhances the potential of PS-InSAR data for SHM, as it provides engineers and stakeholders with a comprehensive and interactive tool to assess deformation patterns, detect anomalies, and support proactive maintenance strategies.



Fig. 5 Final BIM model enriched by PS data

4. CONCLUSIONS

This paper presents an on-going methodological approach for the integration of PS-InSAR data into BIM environments, with the aim of enhancing the structural interpretation of satellite-derived observations. Starting from a processed COSMO-SkyMed dataset, persistent scatterers are georeferenced, instantiated as parametric families, and semantically mapped to the structural components of a masonry arch bridge modeled from a georeferenced point cloud. A custom Dynamo script is developed to automate the integration, enabling the import of PS, the assignment of deformation attributes, and their thematic representation through color coding.

The resulting digital model can be considered a dynamic digital representation in which satellite-derived displacements are directly linked to construction elements and visualized within a realistic and immersive context. In this extended environment, the integration with VR could allow for interactive exploration of deformation patterns in space and time, making the interpretation of satellite monitoring data more intuitive and communicable across stakeholders.

This research represents part of a broader and ongoing methodological experimentation, which aims to establish complex data-integration workflows for infrastructure monitoring. The work is being developed within a research collaboration between Roma Tre University and the TU Delft University of Technology, highlighting the importance of international collaboration in advancing Digital Twin paradigms for Remote Sensing applications.

Although the case study confirmed the feasibility and benefits of the approach, several limitations remain, including the density and spatial distribution of persistent scatterers, residual uncertainties in their precise localization, and the need to complement satellite data with ground-based surveys. Future work will address these aspects while extending the methodology to multi-sensor datasets and real-time integration, with the purpose of developing operational Digital Twin systems that support in real time structural health monitoring.

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