From BIM–SAR Fusion to API-Based Digital Twin Services for Building Deformation Monitoring

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Abstract

The integration of multi-temporal SAR interferometry with Building Information Modelling (BIM) provides new opportunities for object-level deformation monitoring in urban environments. The BIMSAR framework demonstrated the feasibility of linking Persistent Scatterer Interferometry (PSI) results with IFC-based BIM models to derive building-specific deformation indicators. Multi-frequency InSAR data from Sentinel-1, TerraSAR-X, and PALSAR-2 are processed using a PSI-based strategy to derive millimetre-scale deformation velocities and time series. Building on this methodological foundation, this study reports the transition of BIM–SAR fusion toward an API-enabled Digital Twin service, including the delivery of a structured deformation database and the presentation of an interoperable API design for scalable building deformation monitoring. Deformation measurements are semantically associated with BIM objects and, where applicable, building components. The fused information is stored in a structured database that has been implemented and delivered as part of the service development, and is exposed through a RESTful API to provide standardized access to deformation indicators and quality metadata. A pilot implementation in the city of Ahlen, Germany, demonstrates the end-to-end workflow from MTInSAR processing to BIM-linked data storage and API-based digital twin visualization. The results show that deformation time series can be systematically integrated into BIM environments and served through interoperable interfaces, supporting reproducible and scalable geospatial digital twin services for building deformation monitoring.

1. Introduction

Building deformation and structural distress can arise from a wide range of processes, including soil consolidation, groundwater variations, construction activities, aging infrastructure, and locally changing load conditions. For property owners and asset managers, early identification of abnormal deformation trends is essential to support maintenance planning, risk mitigation, and cost-effective asset management. Satellite-based multi-temporal Synthetic Aperture Radar interferometry (MTInSAR) enables millimetre-scale monitoring of surface deformation over large areas and long time periods, providing an attractive complement to conventional inspection and point-based surveying methods (Costantini et al., 2014; Yang et al., 2023).

In parallel, Building Information Modelling (BIM) has become an established standard for representing building geometry and semantics (Volk et al., 2014). BIM data—typically provided in Industry Foundation Classes (IFC) format—contain structured information about building elements, usage, and component hierarchies that can support interpretation of monitoring results. Integrating MTInSAR deformation time series with BIM therefore offers a pathway from point-based deformation measurements toward object-level indicators that can be directly linked to individual buildings and structural components.

The BIMSAR framework (Schneider et al., 2023; Yang et al., 2025) demonstrated the feasibility of linking deformation results derived from Persistent Scatterer Interferometry (PSI) (Devanthéry et al., 2014; Ferretti et al., 2011; Kampes, 2006) with IFC-based BIM models to derive building-specific deformation indicators and to visualize these results within digital twin environments. While this methodological foundation establishes how SAR observations can be associated with buildings and components, operational deployment requires additional capabilities, including structured data storage, reproducible data models, and interoperable interfaces for integration into external software ecosystems.

Practical monitoring services must support standardized access to deformation metrics, quality information, and associated building objects across different user environments, ranging from municipal Geographic Information Systems (GIS) to enterprise property-management platforms. This motivates service-oriented architectures in which monitoring results are stored in a structured database and delivered via application programming interfaces (APIs), rather than remaining confined to standalone research prototypes.

This paper presents the extension of the BIMSAR framework toward an API-based Digital Twin service for scalable building deformation monitoring. The contribution of this study is threefold: (1) implementation and delivery of a structured deformation database linking PSI-derived time series with BIM objects, (2) presentation of a RESTful API design enabling standardized access to building-level deformation indicators and metadata, and (3) demonstration of the end-to-end workflow in a pilot implementation in the city of Ahlen, Germany. The proposed approach supports reproducible and interoperable integration of deformation monitoring into digital twin applications and provides a pathway toward operational services for building owners and property stakeholders.

The remainder of this paper is organized as follows. Section 2 summarizes the BIMSAR framework and selected results from the Ahlen pilot area, including building- and city-scale visualization. Section 3 presents the API-based digital twin architecture, including the database design, API concept, pilot implementation, and deployment considerations. Section 4 discusses the benefits and limitations of the service-oriented architecture. Finally, Section 5 concludes the paper and outlines future development directions.

2. BIMSAR Framework

2.1 Project Overview

The BIMSAR project (Schneider et al., 2023; Yang et al., 2025) was initiated to bridge satellite-based deformation monitoring and BIM within a unified analytical framework. The central objective was to transform PSI-derived deformation measurements into building-level indicators that can be interpreted within digital twin environments.

The framework integrates multi-temporal SAR processing with semantic building representations. PSI-derived deformation velocities and time series are generated for stable scatterers in urban areas and subsequently linked to BIM geometries, typically provided in IFC format. This integration enables deformation attributes to be associated with building objects rather than remaining as isolated radar measurement points.

The Ahlen pilot area situated in the eastern Ruhr region of Germany serves as a testbed for validating the workflow under real-world conditions. The area is characterised by extensive post-mining deformation resulting from historic coal extraction and groundwater rebound. The project demonstrated that millimetre-scale deformation monitoring can be translated into building-centric information products suitable for engineering interpretation and asset-level assessment (Yang et al., 2025).

2.2 Platform - from Building to City Scale

A core contribution of the BIMSAR framework is the scalable platform concept that supports deformation monitoring at multiple spatial levels, ranging from individual building components to city-scale screening. This multi-scale capability is essential for practical use by stakeholders such as property owners and asset managers, who require both detailed building-level interpretation and a broader portfolio- or municipality-level overview.

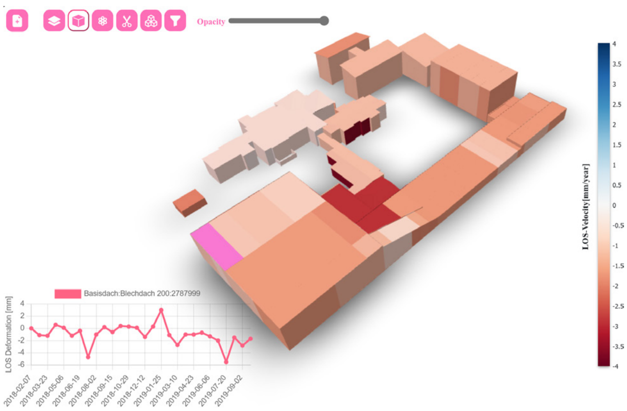

Figure 1. Example of building-scale digital twin visualization showing TerraSAR-X deformation time series linked to BIM building components, enabling object- and component-level inspection of deformation history within a 3D BIM context.

At the building scale, deformation information derived from PSI is linked to IFC-based BIM representations. The platform enables visual inspection of deformation attributes at the level of building objects and, where available, at the level of building components. Figure 1 shows an example of a digital twin visualization in which a TerraSAR-X deformation time series is associated with specific BIM elements, allowing users to inspect object-level deformation history directly within a 3D building context. This representation supports engineering-oriented interpretation, as deformation measurements are no longer presented as isolated scatterer points but as attributes of meaningful building objects.

At the city scale, the same concept is extended to large numbers of buildings by linking PSI measurement points to a city model and providing map-based visualization of deformation patterns across an entire urban area. Figure 2 illustrates the city-scale view for the pilot area, where deformation measurements are displayed as a dense point cloud integrated with a BIM-based city model. This enables rapid screening of deformation hotspots, comparison across neighbourhoods, and identification of buildings requiring closer inspection. The platform therefore supports a consistent workflow in which users can first identify anomalies at city scale and then drill down to building- or component-level time series for detailed assessment.

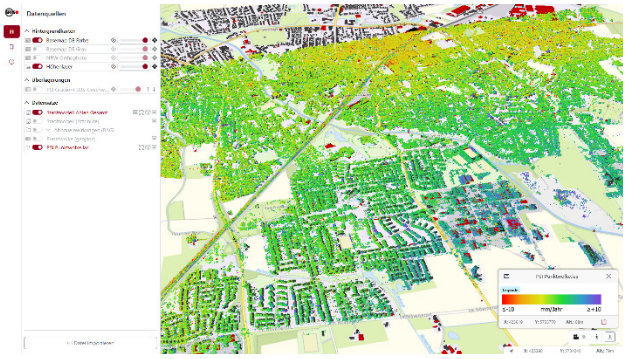

Figure 2. City-scale digital twin visualization integrating a BIM-based city model with PSI point-cloud deformation measurements.

Together, the two views demonstrate how BIMSAR provides a coherent multi-scale digital twin environment for building deformation monitoring and communication: from city-scale screening to building-scale or object-level interpretation.

2.3 Selected Results and Findings

The city of Ahlen represents the city-scale extension of the BIM–InSAR monitoring concept. Monitoring deformation phenomena in this area requires both long-term consistency and sufficient spatial resolution to capture deformation gradients within densely built environments.

The ground deformation derived from TerraSAR-X Sliding Spotlight data exhibits an overall pattern consistent with the EGMS (European Ground Motion Service: https://egms.land.copernicus.eu/) products from Sentinel-1 (Figure 3). A distinct post-mining heave zone is visible southeast of Ahlen. The higher spatial resolution of TerraSAR-X enables detailed deformation mapping that is essential for future BIM integration, while its time-series analysis provides improved precision in estimating deformation trends. Validation against five levelling benchmarks shows an average velocity difference of approximately 1 mm/yr., confirming the reliability of the satellite-based measurements.

Last year, a site inspection was conducted in Ahlen to investigate potential building damage indicated by the deformation analysis (Figure 4). Of particular concern is a primary school building (the Mammutschule), where pronounced wall cracks were observed. The PS-clustering analysis reveals at least five dominant deformation zones on this building. This complex deformation pattern may have contributed to the cracking, or conversely, the existing structural damage may have altered the deformation response. Further joint investigations with structural engineers are planned to clarify the causal relationship.

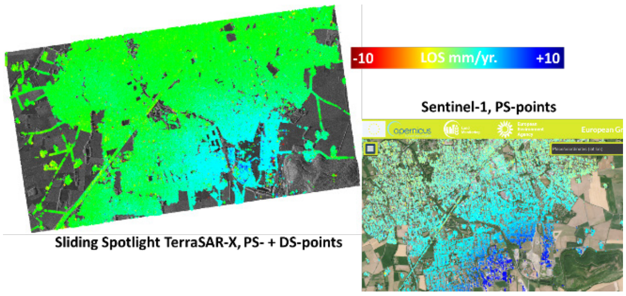

Figure 3. Comparison of deformation velocities in Ahlen derived from TerraSAR-X (Sliding Spotlight, left) and EGMS (Sentinel-1, right).

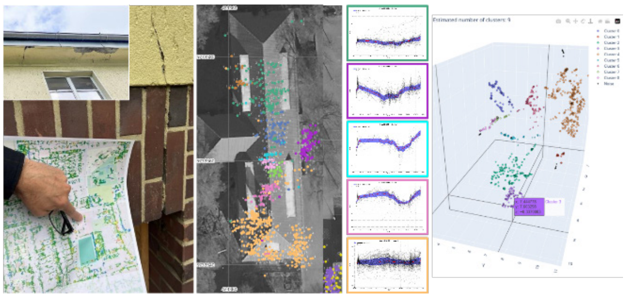

Figure 4. Field inspection and PS-clustering results in Ahlen. Photographs show observed wall cracks at the Mammutschule (top left). The cluster analysis (centre and right) identifies multiple deformation zones corresponding to potential structural stress areas.

Meanwhile, considering the number of different deformation groups with the average, maximum, and minimum deformation for each object or a defined area, potential damage risk for buildings is quantified (Figure 5). High-risk objects are highlighted in red and require follow-up actions such as inspections by authorities or property owners. Such maps make the monitoring task more intuitive and support efficient prioritisation of maintenance efforts.

As mentioned, all datasets have been integrated into a geospatial, GIS-based digital twin environment. The integration represents a key step towards operational, multi-sensor ground-stability services for post-mining regions. This interactive platform combines the deformation results from multiple sensors with 3D city models and cadastral information, enabling seamless spatial exploration and cross-analysis.

The Ahlen pilot confirms that PSI-derived deformation time series can be integrated with BIM and city-scale geodata to support both spatial screening and object-level assessment, thereby improving interpretability compared to point-based deformation maps alone. At the same time, the research platform implementation is primarily optimized for analysis and visualization workflows and is not designed for standardized external access, long-term updates, or straightforward integration into third-party asset-management environments. These limitations motivate the transition towards a service-oriented architecture in which deformation indicators and BIM relations are stored in a structured database and exposed via a RESTful API, which is introduced in the following section.

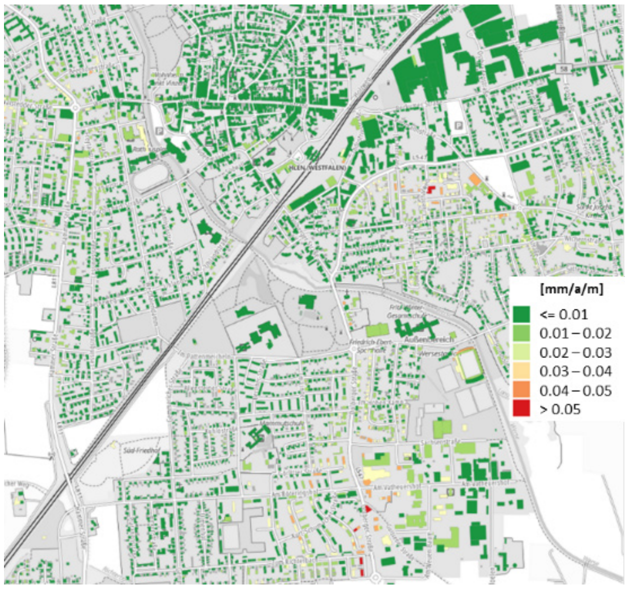

Figure 5. Building-scale risk map of Ahlen derived from deformation gradients. Objects are colour-coded by potential risk level, where red indicates very high risk and warrant further on-site inspection.

3. API-Based Digital Twin Architecture

3.1 Data Model and Database Design

The data model is designed to support structured storage and standardized access to deformation information derived from PSI. Deformation time series and derived indicators are organized in a relational PostgreSQL database, in which each BIM object (e.g. wall, slab, roof) is represented as an individual entity with its corresponding three-dimensional geometry. These objects are associated with deformation attributes such as mean velocity, cumulative displacement, and quality metrics derived from PSI processing.

The database schema establishes explicit relationships between geometric entities and deformation measurements through linked tables using foreign keys. In addition, a shared building identifier enables grouping of multiple BIM objects into a single building entity, allowing consistent aggregation and querying at both component and building level. This object-based data structure supports the transformation of point-based PSI observations into semantically meaningful deformation indicators and provides the foundation for scalable querying and integration via application programming interfaces.

3.2 API Architecture

The API is designed according to RESTful principles, ensuring stateless communication and standardized data exchange. Query results are returned in JavaScript Object Notation (JSON) format, providing a lightweight and widely supported structure for integration into external systems. The endpoint structure follows a hierarchical and consistent design, enabling intuitive access to deformation information at different levels, for example by retrieving all BIM elements associated with a specific building.

The API supports multiple query modes to accommodate different user requirements. In addition to requests based on unique building identifiers, spatial queries can be performed using either point-based searches with a defined radius or bounding boxes, allowing retrieval of all deformation information within a specified area. Each query response includes not only deformation indicators but also associated metadata, such as information on the originating satellite datasets and relevant quality parameters.

To ensure interoperability, the API design follows established standards for geometry representation and coordinate reference systems. Geometric data, including BIM-derived building geometries and component-level representations, are provided in commonly used geospatial formats (e.g. GeoJSON) and standard coordinate reference systems, facilitating seamless integration into GIS platforms, digital twin environments, and external asset-management systems. This standardized and flexible API architecture enables efficient access to deformation information and supports scalable deployment across different application domains.

3.3 Pilot Implementation in Ahlen

The proposed architecture is demonstrated through a pilot implementation in the city of Ahlen, where the structured deformation database has been delivered as a PostgreSQL dump. This format allows straightforward deployment by importing the dataset into an existing or newly created database environment on the client side, ensuring reproducibility and portability of the data.

Based on the defined API architecture, the database can be directly integrated into digital twin environments and geospatial platforms. BIM objects, including their three-dimensional geometries and associated deformation attributes, can be retrieved through standardized API requests and visualized within external systems. This enables consistent representation of building geometries together with deformation indicators, supporting both spatial analysis and object-level inspection.

The workflow is illustrated through example queries that demonstrate access to deformation information at different levels. For instance, all elements associated with a specific building can be retrieved via a request such as /v1/buildings/{id}, while spatial queries can be performed using geographic coordinates and a defined search radius, e.g. /v1/buildings?lat=...&lon=...&radius_m=.... The returned data, including geometry and attributes, can be directly visualized in GIS software such as QGIS or integrated into other compatible systems. This end-to-end workflow highlights the practical applicability of the proposed approach, from database deployment to API-based access and visualization within digital twin environments.

In the pilot workflow, the API is designed to support both object-based and spatial access to deformation information. Object-based access is used when a building or BIM component is already known, for example through a building identifier or component identifier. Spatial access, by contrast, enables users to retrieve deformation information within a defined search area, such as a coordinate with a radius or a bounding box. This supports exploratory analysis where users first identify monitored buildings within a neighbourhood or area of interest and then inspect the corresponding deformation attributes and time-series information.

The returned API response contains the relevant building or component geometry, deformation indicators, time-series attributes, and metadata. This structure allows the same database backend to support different user environments, including GIS software, web-based dashboards, and digital twin platforms. As a result, the pilot implementation demonstrates not only the storage of BIM-linked deformation information, but also its practical delivery through standardized and reusable service interfaces.

3.4 Service Deployment Considerations

The transition from a research platform to an API-based service requires not only a structured database but also a deployment concept that supports maintainability, reproducibility, and integration into external environments. In the presented implementation, the PostgreSQL dump provides a portable baseline dataset that can be imported into a client-side database environment. This enables independent testing, validation, and integration without requiring access to the original processing infrastructure.

For operational use, the API layer can be deployed as an intermediate service between the deformation database and user-facing applications. This separation allows database updates, API maintenance, and visualization development to be handled independently. Such a modular structure is particularly important for long-term deformation monitoring, where new SAR processing results may be generated periodically and must be incorporated into the existing data model without changing the external access logic.

The deployment concept also supports different levels of user interaction. Technical users may directly query deformation attributes and geometries through API endpoints, while non-technical users may access the same information through GIS clients, dashboards, or digital twin viewers. This flexibility is essential for transferring BIM–SAR fusion results from research-oriented demonstrations into practical monitoring services for property portfolios, municipalities, and infrastructure-related applications.

4. Discussion and Outlook

The presented workflow demonstrates how PSI-based deformation monitoring can be extended from a research-oriented BIM–SAR fusion framework toward an operational, service-oriented architecture. By introducing a structured database and a RESTful API, deformation time series are no longer confined to visualization platforms or project-specific environments but can be accessed, queried, and integrated into external systems in a standardized manner. This represents an important step toward embedding satellite-based deformation monitoring into practical asset-management and digital twin applications.

A key strength of the approach lies in the object-based data model, which links deformation measurements to BIM entities and enables consistent aggregation at both component and building level. This improves interpretability compared to scatterer-based representations and supports user-oriented applications such as building screening and prioritization. In addition, the separation of processing, storage, and access layers enhances flexibility, allowing deformation data to be updated independently of visualization environments and facilitating integration into heterogeneous software ecosystems.

However, several challenges remain. The availability and spatial density of PSI measurement points depend on surface characteristics, acquisition geometry, and sensor configuration, which may limit coverage for certain building types or environments. Furthermore, the aggregation of point-based measurements to building objects introduces uncertainties that should be considered when interpreting deformation indicators. On the data integration side, inconsistencies in BIM models, such as missing geometries or non-standardized identifiers, can affect the robustness of the linkage between deformation data and building elements.

Future work will focus on improving the standardization of the data model and extending interoperability with established geospatial and digital twin frameworks. This includes alignment with open data standards such as OGC API Features, CityGML/CityJSON, and Industry Foundation Classes (IFC), as well as the implementation of access control mechanisms and further development of automated workflows for large-scale monitoring scenarios. In addition, the integration of complementary data sources, including cadastral data, building footprint datasets, in-situ monitoring data (e.g. levelling or GNSS), and environmental information such as groundwater or soil data, will be explored. The development of advanced analysis methods, such as anomaly detection or risk classification, will further enhance the applicability of the approach for property portfolios and urban-scale monitoring.

From an operational perspective, the proposed API-based architecture improves maintainability of the monitoring workflow. New deformation products can be inserted into the database without redesigning the visualization layer, while external clients can continue to access updated information through stable API endpoints. This separation between data production, storage, and delivery is particularly relevant for long-term monitoring scenarios, where repeated SAR processing campaigns and periodic database updates are expected. It also enables the same deformation database to be reused by different applications, ranging from lightweight GIS clients to more advanced digital twin environments.

The approach therefore supports a gradual transition from project-specific visualization prototypes toward reusable monitoring services. Instead of delivering deformation results only as static maps or isolated GIS layers, the API-based architecture allows deformation indicators to be queried, updated, and integrated into external workflows. This is especially relevant for property portfolios and urban monitoring applications, where stakeholders may require repeated access to building-level deformation information across different software environments.

Overall, the results indicate that the combination of PSI-based deformation monitoring, BIM integration, and API-based data delivery provides a viable pathway toward scalable and interoperable digital twin services for building deformation monitoring.

5. Conclusion

This study presents the extension of the BIMSAR framework toward an operational, API-based digital twin service for building deformation monitoring. By integrating PSI results with BIM models and structuring the data within a relational database, deformation information can be transformed from point-based measurements into object-level indicators linked to individual buildings and components.

The implementation of a PostgreSQL-based data model together with a RESTful API enables standardized, scalable, and interoperable access to deformation time series and associated metadata. The pilot application in the city of Ahlen demonstrates that deformation data can be efficiently stored, queried, and visualized across different platforms, supporting both city-scale screening and building-level assessment.

The results highlight that the transition from research-oriented BIM–SAR integration toward service-oriented architectures is feasible and provides clear benefits for practical applications. In particular, the proposed approach enables integration into external systems such as GIS platforms and property-management environments, thereby supporting data-driven decision-making for building monitoring.

Future work will focus on extending interoperability with established digital twin and geospatial standards, improving data-model standardization, and enhancing automated analysis capabilities. In particular, further development will address the alignment of the API and database schema with standards such as OGC API Features, CityGML/CityJSON, and IFC-based building representations. This will support more efficient exchange of BIM-linked deformation information between GIS platforms, digital twin environments, and external asset-management systems.

Another important direction is the integration of complementary data sources to improve interpretation and decision support. These may include cadastral information, building footprint datasets, levelling or GNSS measurements, construction records, groundwater information, and soil or geological data. Such datasets can provide additional context for distinguishing between sensor-related limitations, local ground conditions, and potentially relevant structural deformation patterns.

Future developments will also focus on automated update workflows and scalable monitoring concepts. As new SAR time series become available, deformation indicators should be updated in the database without changing the external API structure. This will allow stable access for client systems while supporting periodic monitoring updates. In addition, anomaly detection and risk classification methods will be further investigated to identify buildings or components requiring closer inspection. These developments will support the transition from a pilot implementation toward operational services for property portfolios, municipalities, and urban infrastructure monitoring.

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