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Gradient-Based Analysis of Vertical Displacements in Urban 3D LiDAR Models Using SAR Data

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***Abstract* – This study proposes a method for integrating SAR interferometric data, provided by the European Ground Motion Service (EGMS) under the Copernicus program, with simplified three-dimensional models obtained by combining Regional Topographic Databases (RTDB) and LiDAR (Light Detection and Ranging) data. Historic buildings are represented within the Google Earth 3D environment and classified according to the gradient of vertical displacement velocities calculated from the SAR data. This combination enables not only an immersive and interactive visualization but also a dynamic interpretation of structural changes over time. The historic center of the Municipality of Salerno serves as the test area for the proposed approach. This method offers a simple yet effective tool for monitoring and managing built heritage, making complex analyses more accessible through user-friendly platforms.**

I. INTRODUCTION

The safeguarding of historical and cultural heritage today represents a complex and evolving challenge, in a context where urbanization, climate change, and the obsolescence of traditional techniques threaten the preservation of invaluable heritage assets [1]. In this scenario, the adoption of advanced digital technologies emerges as a strategic response to ensure the protection and transmission of heritage to future generations [2].

Among the emerging solutions, the concept of the Digital Twin (DT) - a dynamic and interactive digital replica of a physical heritage asset—is gaining ground as a revolutionary tool for the monitoring and management of historical sites. By integrating data from IoT sensors, 3D surveys, high-resolution images, and predictive models, the DT enables a comprehensive and real-time understanding of the conservation status of a heritage asset, facilitating preventive maintenance and more targeted restoration strategies [3, 4].

In addition to the DT, complementary technologies such as 3D modeling, augmented reality (AR), virtual reality (VR), and big data analysis are transforming how heritage is documented, studied, and communicated. These innovative graphic representations not only improve the accuracy and efficiency of conservation activities, but also offer new ways of accessing and engaging with heritage, making it more interactive and participatory [5].

Thanks to the evolution of remote sensing technologies and the growing availability of open-access data provided by international programs such as Copernicus, it is now possible to integrate information derived from multispectral and synthetic aperture radar (SAR) analyses into heritage monitoring processes [6]. These data make it possible to detect changes in terms of relative or absolute displacements, degradation phenomena, or environmental changes that are not visible to the naked eye, thus providing valuable support for the preventive conservation and sustainable management of cultural heritage [7]. On this basis, GIS-integrated methodologies leveraging long-term SAR data—such as those implemented in the I.MODI platform—enable precise monitoring of urban structure displacements [8]. These approaches support multi-scale analysis and facilitate the early detection of structural instabilities, thereby contributing to more effective conservation strategies in heritage-rich environments.

The integration of different data sources is crucial to gaining a more complete picture of the state of conservation. By combining information from on-site surveys, satellite data, IoT sensors, and historical archives, it is possible to improve the analysis and planning of interventions, leading to more informed decisions and more effective conservation strategies [9].

In this context, semantic and graph-based methodologies applied to IoT-driven urban monitoring enhance situational awareness and predictive capabilities, which are key elements for managing complex scenarios in cultural heritage environments [10].

However, to ensure that such integration is truly effective, spatial consistency between datasets is essential, especially in 3D modeling processes. Proper harmonization of reference systems and datums is necessary to avoid significant errors in subsequent analyses [11].

Methodologies that exploit the integration of different datasets for 3D modeling, for example, require strict conditions: the spatial data must be framed within the same reference system and be planimetrically consistent. The main issues arise during coordinate transformations between different geodetic datums. Without accurate knowledge of both the source and target datums, transformation errors may reach magnitudes of up to one meter. This work aims to explore the integration of various open-source datasets, with a particular focus on the use of accessible tools such as Google Earth, Quantum GIS (QGIS), and other open source geospatial platforms for the visualization and analysis of historical heritage. The goal is to promote the use of digital tools that enable advanced and interactive graphical representations, useful not only to specialists but also to a broader audience, thus encouraging more inclusive and informed engagement with cultural heritage.

In conjunction with these technological advancements, international institutions such as UNESCO and ICOMOS are increasingly advocating for the adoption of digital tools to support the safeguarding of cultural heritage. These organizations emphasize the role of emerging technologies in improving conservation, documentation, and management strategies. Furthermore, the active involvement of local communities and stakeholders is becoming increasingly important, as digital platforms offer new opportunities for participatory approaches and public engagement. Within this framework, the integration of heterogeneous datasets and open-source geospatial platforms contributes to a more holistic and sustainable management of heritage assets, strengthening the connection between society and its cultural legacy.

II. METHODS

In the field of digital technologies applied to cultural heritage, the method introduces a new approach for the three-dimensional metric representation of historic buildings by integrating 3D visualization with differential displacement analysis derived from satellite interferometry. This combination enables not only a structured and navigable use but also a dynamic interpretation of structural changes over time.

Satellite interferometry allows the relative movements of ground and structures to be measured with millimeter accuracy. This capability is particularly useful in cases of subsidence, where monitoring ground movement is essential to prevent structural damage and ensure the integrity and stability of buildings.

The spatial and descriptive information contained in the Regional Topographic Database (RTDB) and the 3D data from the LiDAR survey of the Ministry of the Environment and for Protection of the Land and Sea (MATTM) can be integrated to generate 3D models of the built environment, suitable for use in the Google Earth 3D platform [11]. These two datasets, being of different types, require proper integration.

This section describes the methodology used for processing SAR data and calculating the gradient of vertical displacement velocity. The gradient helps identify areas at risk of damage, which therefore require increased attention. The three-dimensional urban environment, obtained by integrating the RTDB with LiDAR data, is then classified according to the detected vertical displacement gradients. The results are presented through an interactive visualization in Google Earth 3D, facilitating spatial analysis and displacement assessment.

The process consists of the following steps:

(i) calculation of the vertical displacement velocity gradient separately along each grid direction, particularly along latitude and longitude, using interferometric SAR data;

(ii) extrusion of RTDB polygons corresponding to buildings;

(iii) classification of buildings based on the magnitude of vertical displacement gradients;

(iv) visualization in Google Earth Pro.

Figure 1 illustrates the adopted methodological workflow.

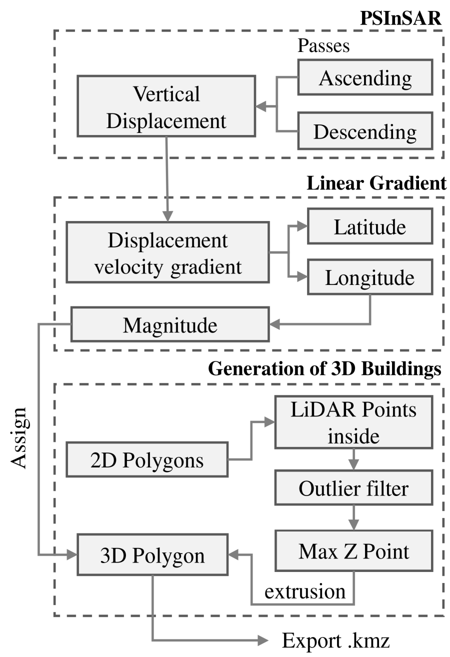

Fig. 1. Workflow

A. Satellite Interferometry

The interferometric technique allows the measurement of the strain component along the Line of Sight (LOS) connecting the satellite sensor to the target on the ground [12], enabling the detection of whether a point on the Earth's surface has moved closer to or farther from the sensor. Therefore, measurements obtained through multi-temporal SAR interferometry represent only a projection of the actual displacement vector along the LOS. Consequently, the greater the deviation of the actual displacement direction from the LOS, the smaller the component detected by the satellite; in cases of deformation orthogonal to the LOS, the measured component is zero.

This limitation means that a single interferogram provides only one component of surface deformation along the LOS. To partially overcome this limitation, the PSInSAR (Permanent Scatterer Interferometric Synthetic Aperture Radar) technique utilizes all available SAR acquisitions over a given area to identify so-called Permanent Scatterers (PS), i.e., targets that maintain stable electromagnetic characteristics over time. For each PS, a displacement time series can be reconstructed with millimeter precision, expressed in mm/year [13].

SAR platforms operate along both ascending and descending orbits: due to the Earth's rotation and the constant orientation of the antenna relative to the flight direction, the same area can be observed from the east during descending passes (north to south) and from the west during ascending passes (south to north). Combining acquisitions from both directions not only helps reduce geometric distortions but also enables the estimation of the vertical component of displacement, which is particularly useful for analyzing subsidence phenomena [7, 14].

The SAR data used in this study were obtained from the European Ground Motion Service (EGMS), part of the Copernicus Programme, which provides interferometric data acquired by the Sentinel-1 mission.

B. Calculation of the Linear Gradient

The calculation of the linear gradient allows the determination of changes in vertical displacement velocity along a specific direction—for example, along meridians and parallels in a geographic coordinate system between two grid nodes.

The gradient in the chosen direction is calculated as the difference in vertical displacement between two grid nodes, divided by the distance between the nodes:

$$g = \frac{S_{(i+1)} - S_{(i)}}{D_{(i),(i+1)}} \qquad (1)$$

where $S_{(i)}$ is the vertical displacement at the i-th grid node, and $D_{(i,i+1)}$ is the distance between two consecutive nodes along the analyzed direction.

In this way, the displacement velocity gradient is calculated for each pair of nodes in the grid and along the main grid directions. The gradient calculation was implemented in MATLAB.

C. Generation of 3D Buildings

The reconstruction of the three-dimensional model of buildings is carried out in the QGIS environment using elementary volumes. An elementary volume is a solid generated by extruding a surface—called the extrusion surface—vertically to a given elevation, referred to as the extrusion elevation. Since extrusion heights are expressed as absolute values, the direction of extrusion may be either upward or downward, depending on the case.

The building polygons contained in the RTDB lack accurate elevation information [11]; therefore, they are used solely as “footprints” for the subsequent extrusion operation. The extrusion elevation is determined using LiDAR data from MATTM.

Specifically, the extrusion process involves the following steps:

1. extraction from the RTDB of 2D polygons related to the built-up area layer;
2. selection of LiDAR points within each built-up area polygon using spatial join;
3. elimination of points not belonging to buildings and possible outliers;
4. extraction of the point with the maximum elevation;
5. assignment of the elevation to the built-up area polygon.

Since the reference systems of the products used differ, coordinate/Datum transformations are required and must comply with the specifications established in the national framework. These transformations were carried out using grids provided by the Istituto Geografico Militare – IGM (in *.GK2 format), each covering the extent of one sheet of the 1:50,000 scale map of Italy.

III. RESULTS

The gradient of vertical displacement velocities was calculated using data provided by the EGMS service. EGMS offers ground deformation measurements derived from Sentinel-1 radar images processed with the PSInSAR technique. The platform allows downloading PS data from both ascending and descending acquisition geometries, available in calibrated and uncalibrated versions. Additionally, it provides products obtained by combining the two geometries, specifically the vertical displacement component and the horizontal displacement along the East-West axis.

The calibrated products refer to a reference model built using GNSS time series available at the European scale. This ensures that the measurements are expressed as absolute values rather than relative ones, making them directly comparable across different geographical areas.

The vertical movement components are referenced to a regular grid composed of square cells approximately 100 m × 100 m in size. Each cell is assigned the average value of the ascending and descending measurements contained within it. These averages serve as input for the decomposition process required to extract the vertical displacement component.

Negative displacement values along the LOS indicate movement away from the sensor; in the vertical component, these correspond to subsidence.

In this study, vertical displacements derived from the combination of ascending and descending calibrated acquisitions were analyzed. The data cover a time span of approximately four years, from 07/01/2019 to 18/12/2023, and pertain to the historic center of the city of Salerno (Italy).

Figure 2 shows a map of the grid nodes with their associated average vertical displacement velocities, calculated as the slope coefficient of the linear regression applied to the measured deformations over the considered period. Within the study area, the average vertical velocities reveal sectors experiencing subsidence up to approximately 10 mm/year and others exhibiting uplift up to about 4 mm/year.

The maximum observed gradient, equal to 0.005 mm/m/year, was calculated along the East and North directions, as described in section II.B. Figure 3 presents two-dimensional building polygons, extracted from the DBTR, classified according to the magnitude of the gradient in the two main directions. Although this value may appear modest, over a distance of 100 meters and a period of 10 years it can generate a non-negligible cumulative displacement. In ordinary or modern contexts, this value might be of limited significance; however, in historic or valuable buildings, even minimal deformations can compromise the stability of fragile or already damaged elements. In less valuable buildings, the effects may be less critical for conservation but are not necessarily negligible - their impact depends on the building's use, pre-existing degradation, and function.

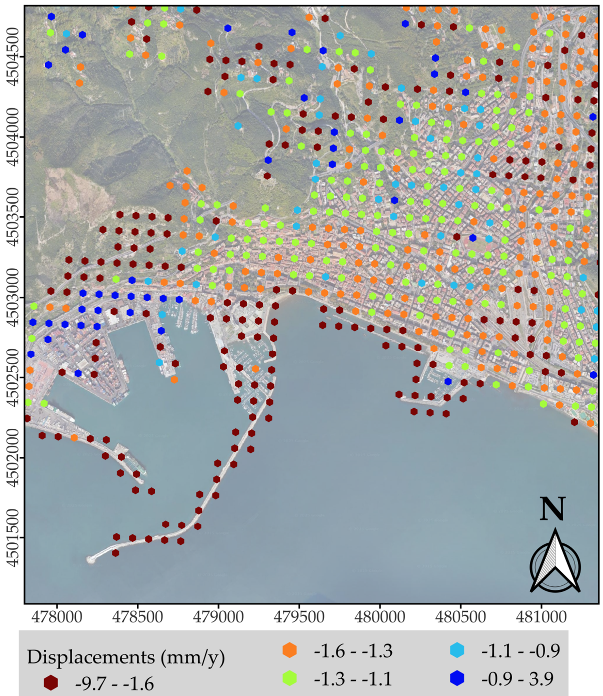

Fig. 2. Map of the average annual vertical displacement velocities (mm/year) at grid nodes. Reference System: EPSG 7792. Base map: Google.

Applying this analysis in urban contexts, particularly within historic centers, proves especially effective for structural monitoring and for planning targeted conservation interventions. For this reason, attention should be paid even to seemingly small variations, especially if they persist over time.

To further enhance the interpretative value of gradient analysis, it is essential to critically assess the thresholds used to classify displacement severity. In historic urban environments, structural sensitivity is highly variable and depends on construction techniques, material properties, and the presence of pre-existing damage. Even gradients that appear low in absolute terms—such as below 0.005 mm/m/year—may indicate potential vulnerabilities when applied to heritage buildings. Vertical displacement rates below 1 mm/year are generally regarded as physiological, while rates between 1–5 mm/year warrant attention, and those exceeding 5 mm/year may signal structural risk. Translating these values into gradient thresholds, a preliminary classification may include: negligible (<0.001 mm/m/year), cautionary (0.001–0.003 mm/m/year), and critical (>0.003 mm/m/year). Although these thresholds are neither normative nor supported by specific scientific foundations, they are consistent with monitoring practices and reflect the need for heightened sensitivity in heritage contexts. Establishing such context-specific ranges could improve the diagnostic precision of the method and support more informed conservation strategies. This approach would benefit from interdisciplinary input, combining geotechnical assessments, architectural surveys, and historical documentation to refine the correlation between gradient magnitude and structural risk.

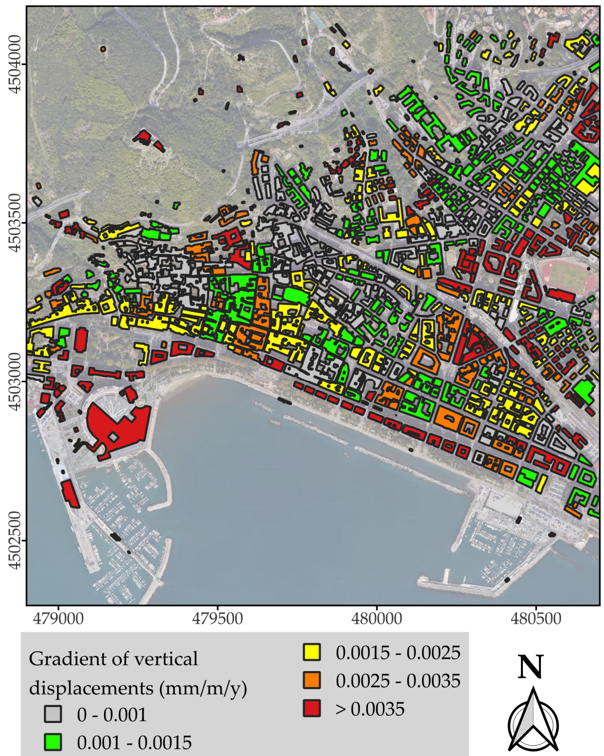

Fig. 3. Magnitude of the average annual vertical displacement velocities (mm/year) associated with building polygons extracted from the RTDB. Reference System: EPSG 7792. Base map: Google.

Each building was assigned the highest elevation among the LiDAR points located within its respective 2D polygon. This step was performed by creating a new field within the polygons containing the maximum elevation value, which was then used to assign the elevation to each building. Each polygon was extruded vertically based on the difference between the maximum elevation (derived from the LiDAR points) and the ground elevation obtained from the DTM (Digital Terrain Model). Elevations are orthometric and referenced to the ITALGEO2005 geoid.

This procedure enables the generation of simplified yet sufficiently representative three-dimensional models, suitable for integration within 3D GIS environments or interoperability with simplified BIM environments. Subsequently, the buildings were exported in KMZ format, with their respective elevation values associated with each element. Each 3D polygon maintains a link to the data in its attribute table.

Figure 4 illustrates the three-dimensional representation of the buildings in Google Earth Pro.

Fig. 4. Three-dimensional representation of buildings in Google Earth Pro, classified according to the magnitude of the vertical displacement gradient.

This type of visualization, beyond being effective for communication purposes, is particularly useful in the context of digital technologies applied to cultural heritage. The proposed method allows the integration of 3D analysis with differential displacements estimated via the gradient, thus providing an intuitive approach for assessing the conservation status of historic built heritage.

The platform also enables integration of additional information (such as historical, architectural, or geotechnical data), making the virtual environment a comprehensive and accessible tool for documentation, monitoring, and enhancement of built cultural heritage.

IV. CONCLUSIONS

The integration of satellite interferometric data, three-dimensional building models, and visualization tools such as Google Earth Pro represents an innovative and promising approach for the monitoring and enhancement of the built heritage. This method not only facilitates the spatial analysis of displacements and the identification of structurally at-risk areas but also allows for a more immediate and visual understanding of the buildings' constructive and functional characteristics through the direct observation of volumetric shapes, heights, and planimetric geometries.

This interpretative capability proves particularly valuable in the field of conservation and heritage management, as building morphology can provide essential insights into the intended use and the construction systems adopted over time. The classification of buildings based on vertical displacement gradients, combined with 3D modeling using DBTR and LiDAR data, constitutes an effective tool for the prevention and management of structural risk.

Overall, the proposed method constitutes an integrated and multidisciplinary solution for the documentation, monitoring, and communication of the value, vulnerability, and conservation status of cultural heritage, providing fundamental support for both protection activities and territorial planning.

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