MULTI-MODAL/MULTI-RESOLUTION 3D DATA ACQUISITION AND PROCESSING FOR A NEW UNDERSTANDING OF THE HISTORICAL CITY OF SIENA (ITALY)

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ABSTRACT:

The paper presents the acquisition and data processing approach for the Ground Penetrating Radar (GPR) and laser scanner surveys carried out within the SOS project (the acronym comes from 'SOtto Siena', in English 'Beneath Siena'). SOS is a program aimed to overcome some of the problems and limitations currently present in the study of cities with long-term continuity of life, responding in particular to the need for a better understanding of the city's ancient fabric and hence to improvements in its conservation by: GPR city survey full coverage (of all the public spaces, streets, squares, courtyards, gardens, etc.), GIS data entry of the historical-archaeological and geoarchaeological knowledge and the development of a 3D Archaeological WEBGIS.
The paper discusses the procedure for the creation of a 3D viewer within an already active WEBGIS platform, specifically created for the visualisation and management of archaeological data. The GPR data, once acquired, were exported in 3D in the form of point clouds and subjected to a procedure of cleaning and filtering from noise, so as to eliminate geometries not referable to anomalies and therefore to the presence of buried structures or cavities, and then transformed into mesh to meet the needs of the subsequent process of semantic enrichment. The GPR survey of the underground was flanked by laser scanning of some of the most significant structures in the historic centre (e.g. the cathedral). All 3D geometries were then inserted into the new visualiser via a pipeline using open-source tools and libraries.

1. INTRODUCTION

The study, conservation and protection of an historical city centre is a challenging task, which ought to consider the needs for unremitting modification that characterise the life of any inhabited centres and, at the same time, the conservation issues of the historical heritage. The SOS Project (the acronym comes from '*SOtto Siena*', in English 'Beneath Siena'), promoted by the Tuscan region and coordinated by the University of Siena in collaboration with the Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Siena, Grosseto and Arezzo (SABAP-SI), in partnership with the Municipality of Siena started with the aim of overcoming some of the problems and limitations present in the study of historical cities, responding in particular to the need for a better understanding of the city's ancient layout and hence to improve its conservation. The objectives of the project are very ambitious and are based on mapping the archaeological and historical continuum of the city, offering an outstanding tool for the understanding, planning and management of an historical city (Campana *et al*. 2023).
The project partners' have identified and developed three main lines of action:
• The systematic acquisition and processing of Ground Penetrating Radar (GPR) measurements of all the public spaces in Siena, such as streets, squares, courtyards, and gardens that are, at least theoretically, accessible for the mapping of archaeological features and utilities down to a depth of about 2 m and over an estimated 25 hectares of surveyable area.
• The implementation of a comprehensive data entry. In particular, the historical-archaeological and geoarchaeological knowledge and the archaeological interpretation of GPR datasets.
• The development of a 3D Archaeological WEBGIS aimed to manage, integrate, share, and update data and information. The system has been designed to be accessible by all the institutions in charge of research, conservation, planning and management of the city (University of Siena, SABAP-SI and the local administration).
The 3D WEBGIS has been based on SITAR, a GIS implemented by the Superintendence for conservation purposes to manage the archaeology of the city of Rome starting from 2007 (https://www.archeositarproject.it/, Serlorenzi 2019). Nowadays, SITAR constitutes one of the most successful and long-lasting WEBGIS available in Italy. The system is based on a complex relational database and 2D maps. Instead of developing yet another GIS, we implemented an agreement with the Superintendence of Rome cloning and customising SITAR into SITAS (the WEBGIS of the city of Siena); furthermore, we developed an entirely new tool aimed to the management and visualisation of 3D data allowing us to have a comprehensive assessment of the subsurface features (surveyed by GPR) together with the standing architecture (achieved by 3D recording and modelling). This paper illustrates how we captured information by using different techniques and then combined digitally to answer key questions regarding the understanding of the past of Siena and urban planning. In particular, we focused on GPR data acquisition, data processing,

visualisation and semantic interpretation within the framework of SITAS. The paper will also emphasise how the 3D WEBGIS plays a substantial role in the understating of the past as well as in the management of the historical city of Siena by the visual integration of underground features detected by GPR and aboveground building evidence mapped by modelling 3D city blocks and by laser scanning (Schmidt *et al.* 2023).

2. CITYSCAPE 3D SURVEY: UNDER/ABOVE GROUND STRUCTURES/FEATURES

2.1 GPR survey

IDS's StreamUP system (fig.1) was used for the collection of GPR survey data. This is a state-of-the-art georadar system capable of providing high quality and productivity in performing real-time subsurface surveys. It is a multi-channel, multi-frequency (200MHz and 600MHz), dual-polarization (longitudinal VV and transverse HH) system dedicated to subsurface analysis over large areas that facilitates data acquisition and processing. The streamUP is towed by a vehicle, and in the SOS project an electric vehicle was used that can also operate in an urban environment without slowing down traffic or being a nuisance to citizens. During the survey operations, the georadar data acquisition software simultaneously manages data from topographic instrumentation in order to record the position of the antenna during the various scans.

Given the geomorphological complexity of the context under investigation, the topographical survey played a fundamental role in the correct management and integration of the data acquired. In order to collect, process and interpret the data, it was necessary to record the position of each geophysical measurement by means of a detailed plano-altimetric survey with the aid of a Total Station (Leica TS50). The coordinates were then converted using a topographic GNSS (Leica GS18), into WGS84, UTM 32N. Only in the case of the magnetic measurements of the Piazza del Duomo the data were acquired directly using a GNSS positioning system.

The processing of GPR data was implemented by IDS IQMaps software and by Screening Eagle Technology GPR-Slice software; this yielded 2D (B-scan sections and time-slices) and 3D (point cloud GPR volume) results, which allowed us to visualise and locate underground dielectric anomalies.

The georeferenced GPR volume was exported from GPR-Slice as a text file point cloud, and further processed through the open source software CloudCompare. In this environment, the point

Figure 1. Survey activities by IDS STREAM UP

cloud was subjected to a clean-up procedure, to reduce as much as possible background noise and extract high-energy anomalies. This approach allowed us to introduce a substantial innovation: interpreting the dataset and mapping subsurface

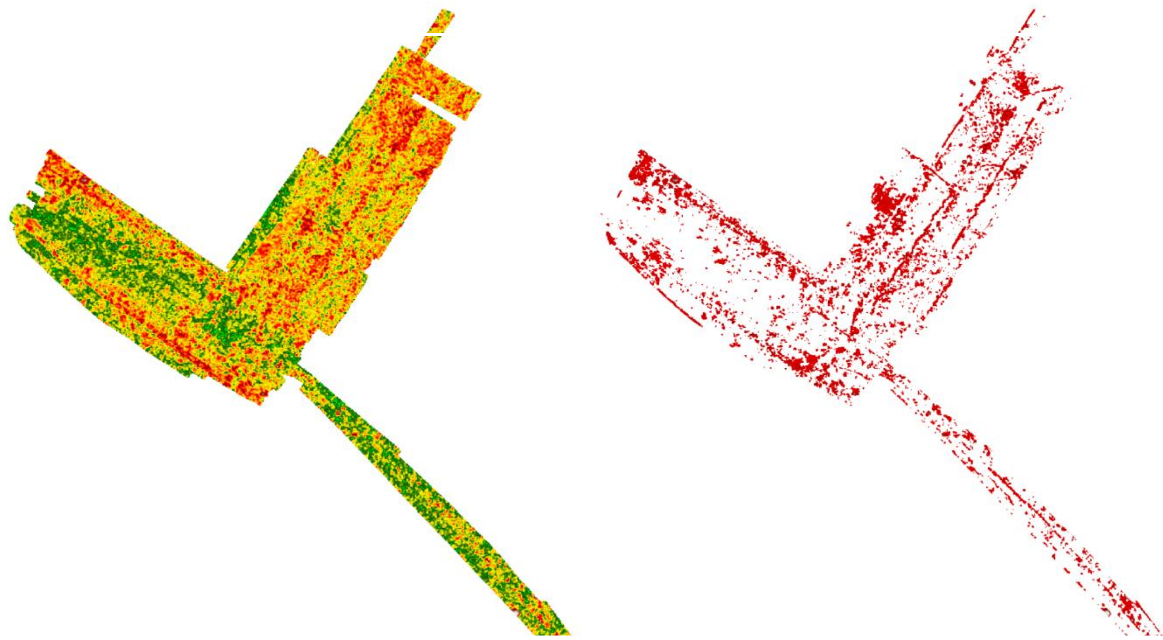

Figure 2. An example of a point cloud from the GPR survey, before (left) and after (right) the noise-filtering process in Cloud Compare.

features in 3D instead of - as usually happens - interpolating the original data by 2D time slices losing a substantial component of the original dataset.

As the exported GPR volume retains the intensity of dielectric reflection as a scalar field (obtained with the Hilbert transformation processing in GPR-Slice), this parameter represents the first step of the point cloud filtering pipeline. Through scalar field filtering (operated manually on the scalar field histogram in CloudCompare) most of the low-energy background geometries were isolated and eliminated, separating smaller point clouds which belong to recognisable anomalies.

A further clean-up passage was achieved with SOR (Statistic Outlier Filtering), which eliminates point aggregates that are sparse and far from larger structures.

2.2 GPR data processing

By fine-tuning all parameters involved in the filtering procedure, a smaller and less dense point cloud was obtained, containing all high-energy GPR anomalies (fig. 2).

To ease the meshing algorithm, this point cloud was segmented into smaller entities with the segmentation tool of CloudCompare: this step, too, required a process of fine-tuning to find the optimal parameters and yield reasonable geometries. These geometries were then computed normals. Given the WEBGIS platform's needs to work on volumetric entities during the semantization process, the point clouds were also remeshed through Poisson triangulation method (Plugins > PoissonRecon) and cleaned-up following the process of filtering to eliminate outlier geometries already used for the point clouds.

A further step was the export of the 3D meshes in a format that could be used in the 3D visualizer. As explained in the next section, the 3D visualiser was developed using the open source components of the Cesium.js library, which requires the use of files in specified vector formats, including shapefiles. This, however, is not a supported format for exporting meshes to Cloud Compare. An intermediate step was therefore necessary to achieve the conversion of the volumes: the meshes were first exported in .ply format and then converted to shapefiles using the ArcGIS Pro software and its 3D Analyst extension.

Following the processing and evaluation of the measurements, the data revealed the presence of numerous anomalies attributable in particular to underground utilities, evidence of archaeological interest and a number of features of uncertain interpretation.

2.3 3D Laser scanner survey and city model

In addition to the GPR surveys, some acquisitions were also carried out with the Leica Geosystems RTC360 Laser Scanner, which particularly involved the area of the Piazza del Duomo. The scans were carried out at medium resolution with coverage at 10 metres of 12 mm and at medium resolution with coverage of the scans at 10 metres of 6 mm. The georeferencing of the survey was carried out by integrating the measurements with the total station, set on the same coordinate system already used for the GPR survey (WGS84 UTM 32N).

In addition to the data obtained through the laser scanner survey, it was also possible to retrieve a dataset created in the past by the municipal administration and including all the information useful for the implementation of a procedural 3D model of the historical buildings in the centre of Siena. This dataset, together with the point clouds collected by laser scanning, constituted a substantial dataset for the visualization of the cityscape and a better understanding of the evidences gathered by GPR survey.

3. SITAS WEBGIS AND THE 3D VISUALIZER

As a result of this pipeline, the development of an innovative visualisation tool allowing the simultaneous analysis of above and underground structures was needed (fig. 3). The development of a 3D geographic environment was also aimed at providing a more complete view of the complex reality that characterises historic city centres and enabling better planning of maintenance and protection measures for the city's heritage. The 3D WEBGIS platform has been implemented starting from SITAR WEBGIS architecture ensuring a comprehensive and flexible system. Indeed, open-source and free 3D visualisation software such as SketchUp and CloudCompare, are limited in terms of contextual study and data integration. As Spreafico et al. refers, 3D models are often used as individual models detached from their context, with no relation to other cultural heritage and relevant natural environment; however, digital technologies such as WEBGIS enable researchers to access and analyse ephemeral cultural heritage structures in all their

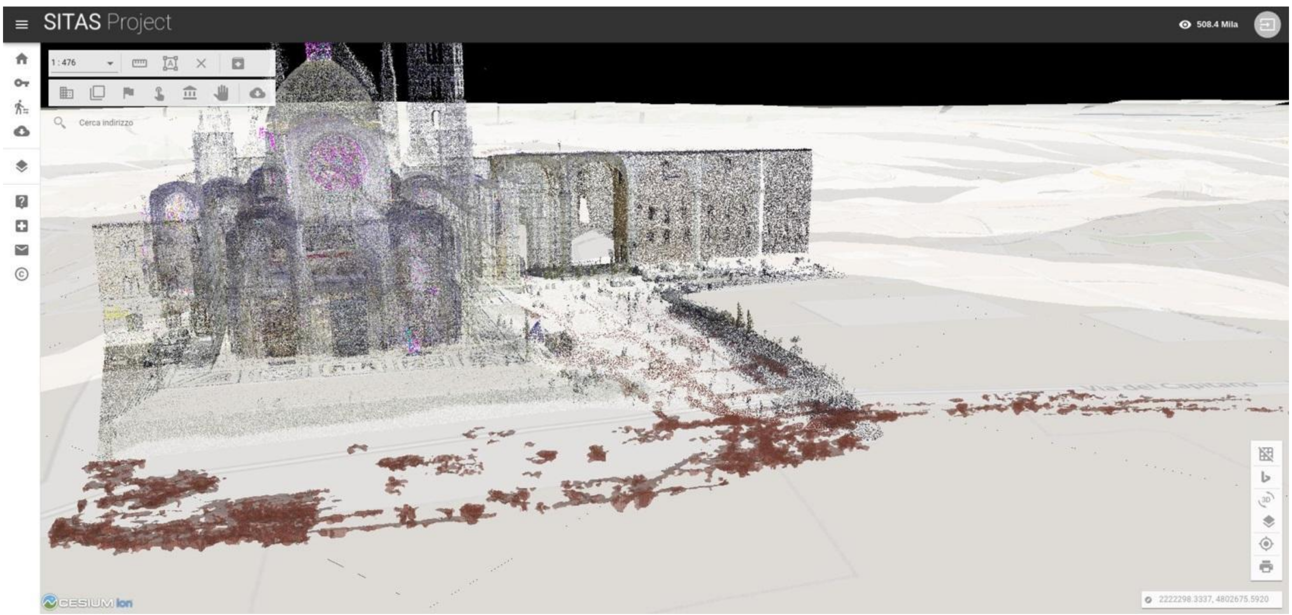

Figure 3. The visualisation of 3D elements (point clouds and meshes) in the SITAS framework.

complexity by providing contents for any other user to access and utilise. (Spreafico et al, 2023) The switch between the 2D and 3D viewer, which was achieved by using open-source and free technologies, provided a wider context for the analysis of 3D meshes and point clouds with the existing geospatial data on the WEBGIS application. *Cesium.js* library was adapted to create the 3D map, containing the Digital Elevation Model, the interface between underground features and aboveground structures, in addition to imagery and other layers. On the other hand, the large geospatial dataset of Siena's city centre buildings, the archaeological structures, point clouds, and underground utilities, were represented as 3D tilesets, and efficient rendering of different tileset formats, including b3dm and point clouds, was succeeded through their organisation in hierarchical structures as the tree, each of which required specific generation methods.

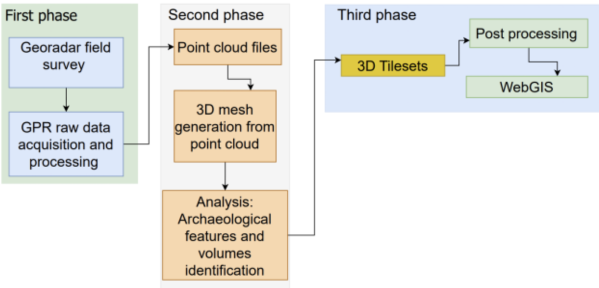

Figure 4: 3D survey data processing and 3D tilesets generation

The workflow in fig. 4 displays how the 3D survey data is processed and converted into 3D tilesets suitable for rendering on the 3D viewer.
The output of the second phase, explained in detail in the previous section, is the geospatial data with different file formats. The exported data is manipulated and converted into 3D tilesets with Cesium.js library.
Cesium is a library for multidimensional data visualisation, including the drawing of a 3D Earth based on the WGS84 ellipsoid with overlaid Digital Terrain Model data, as well as 3D objects that may change their state (e.g., position or animation frame) over time (Kulawiak et al. 2019). Hence, it is used for creating 3D maps and 3D tilesets providing a solution for the automatic construction of underground assets (3D meshes, digital objects) from the point clouds that are exported as 3D vector data in addition to their metadata.
3D map integration and diverse geodata formats insertion on the viewer could be easily done with the commercial version of Cesium while the free version required the exploitation of third-party libraries, tools, and plugins to access Cesium entities and functions. Since it was one of the software architecture's requisitions, the 3D viewer development and 3D tilesets uploading are handled with open-source and free technologies. Additionally, the Cesium.js library offers open-source tools that can perform cross-platform operations, run on multiple computers and mobile devices and different operating systems, and provides a visualiser for complex geospatial 3D data with real-time updates and interactivity (Liu et al. 2023). So, the buildings' data and 3D survey data whose format are shapefiles, are converted into 3D tilesets to treat them as Cesium entities by using free-open source solutions and later on uploaded and managed by Cesium functionalities on the 3D viewer.

3.1 3D Tilesets

According to Cesium 3D Tiles Specification, a tileset is a set of tiles organised in a spatial data structure and includes Hierarchical Level of Detail, meaning the tiles are rendered according to their importance depending on their geometric error (Cesium Team, 2018). The necessary information such as geometric, spatial, and semantic data of each tile is stored in its

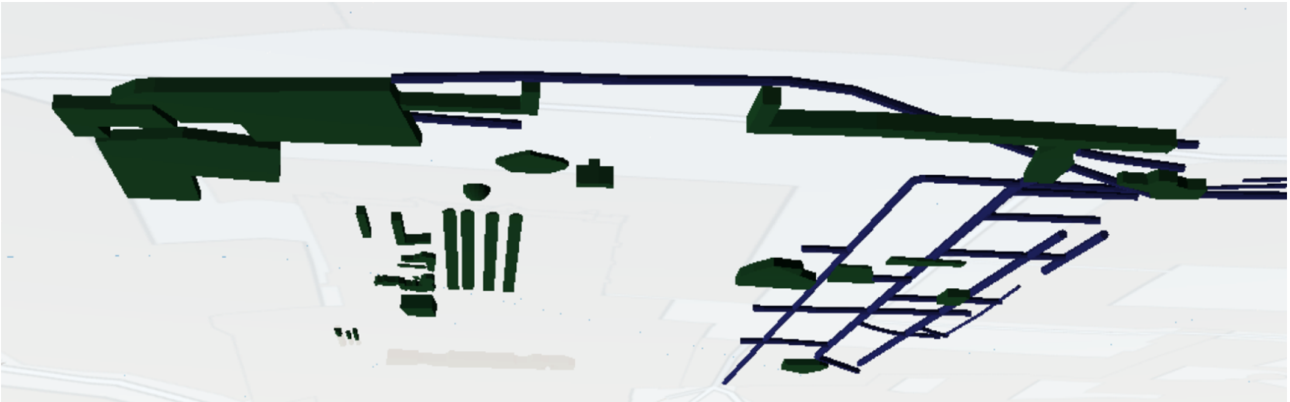

Figure 5. Underground Structures in the 3D viewer

Figure 6. 3D model of Siena's city center in the 3D viewer

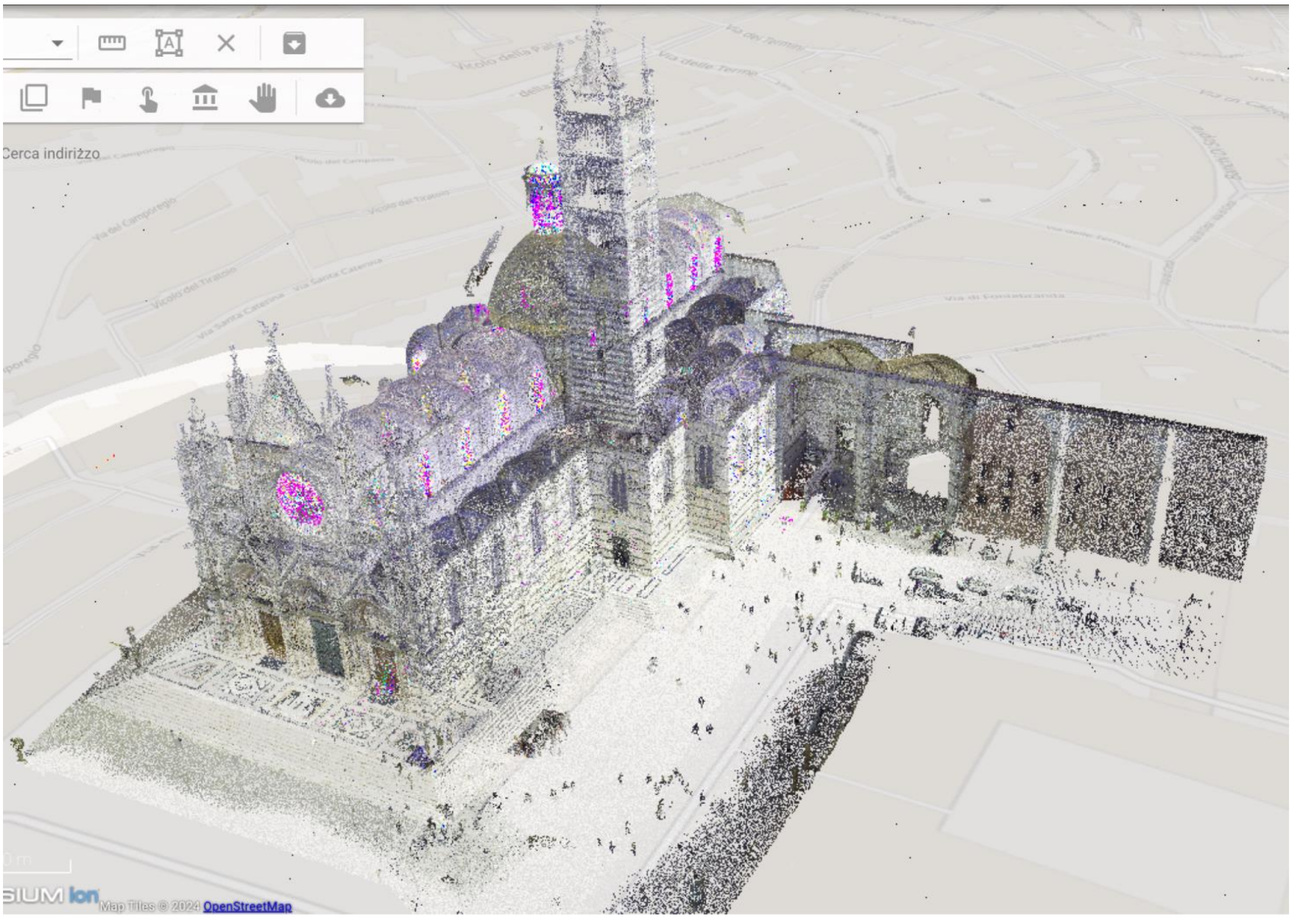

Figure 7. Duomo's point cloud representation in the 3D viewer

batch table. Their properties, such as coordinate system, model geometry and texture information, can be set and modified.
The tilesets are grouped as Batched, Instanced 3D model, Point cloud, and Composite, and generated from vector data such as Shapefiles, GeoJSON, CityGML and point cloud files. Geospatial data, classified as point clouds along with buildings, archaeological structures, and underground services (fig 5 and 6) on the system, is built as b3dm tile model from 3D geometries located on the PostgreSQL database.
Lastly, the point clouds obtained from the laser scanner survey, which contain the geographic position and RGB attributes of millions of points within a single binary file, are other types of 3D tilesets inserted in SITAS (fig. 7). The high level of accuracy portraying the real-world objects in WEBGIS environment increases the usefulness of the point clouds providing detailed representations besides facilitating the spatial analysis.
The datasets consisting of individual points positioned on a 3D map enhance the interactive visualisation to explore and analyse the cultural heritage assets.

3.2 3D Visualisation

The web-based platform provides combined and smooth experience while navigating bi and tri-dimensional data. The toggle system between 2D and 3D map (fig. 8) as well as between various archaeological features and volumes within a single view enhances the user-centric experience.
Cesium renders map data from different sources such as web map services or OpenStreetMap. By making use of the Cesium ion option, the 3D map can be easily activated by including the Viewer component as the base entity on the application. On the other hand, the 3D viewer of the SITAS is built with OpenLayers so OSM is integrated through the ol-cesium library (https://github.com/openlayers/ol-cesium) which principally takes the 2D map as the base map and activates the 3D one. Differently from the commercial access of Cesium, the Cesium's Scene entity is deployed, instead of the main Viewer. However, this hasn't constricted the uploading and management of 3D tilesets.
Altogether, the interactive mapping component is a tool for some operations such as zooming, navigation controls, retrieving information and uploading 3D meshes to visualize on the 3D viewer. Toggling imagery and terrain layers contribute to the flexibility and the contextualization of the geospatial data while a compass is included for orientation within the 3D environment. Moreover, some other map operations as the distance and area measurements on the 3D map can be done through Cesium functions for the distance measurement and through turf.js for the area measurement.

3.3 Methodology

First, the Digital Elevation Model on the 3D map is inserted for accurate positioning and visualisation of the 3D models and point clouds on the 3D map. The free version of the Cesium library doesn't allow the upload of the DEM on the 3D viewer directly. For this reason, the Geoserver Terrain Provider plugin which is published on GitHub (https://github.com/kaktus40/Cesium-GeoserverTerrainProvide) and renders elevation data such as bil, png, and gif formats deployed on the 3D map in addition to other terrain and imagery layers. The terrain layer's processing starts with the conversion of the ascii file to geotiff by using gdal_translate. The output file is added to GeoServer, on which is installed the DDS/BIL

plugin, giving the possibility to modify the imported tiff file’s encoding so that it is suitable to be handled by the plugin.
Secondly, as shown in fig. 9 3D tilesets as b3dm tile models are generated by utilising data processing tools such as the ogr2ogr tool (GDAL/OGR contributors, 2023) to import the shapefiles on the database and pg2b3dm tool (https://github.com/Geodan/pg2b3dm) that receives the geometry from PostgreSQL database as a polygon, eliminates the invalid geometries, converts it to a polyhedral surface by triangulating it and exports bd3m files and a JSON file with attribute information.
The 3D tilesets generation of the GPR survey meshes and the 3D buildings from shapefiles demands different data processing due to their geospatial data containing different types of geometries. The usage of the tessellation tool has been necessary to manipulate the buildings’ vector data and to convert the geometries to triangulated polyhedral surfaces so that they are suitable to be handled by pg2b3dm. The problem with the generation of 3D tilesets directly by using pg2b3dm tool is that 3D tiles move when the camera tilts because the geometries saved in buildings’ shapefiles are multipolygons, while pg2b3dm tool requires triangulated polyhedral surfaces containing 3D geometries. The buildings data, imported to the database as multipolygons, have among their attributes the x and y position and altitude, divided into columns. The tessellation tool creates triangulated polyhedral surfaces from the height value of the buildings but does not consider the altitude information. To solve this problem, the tool is modified by adding an option for the Z column; afterwards, the buildings are positioned on DEM correctly.
The operations for the buildings include the elimination of the invalid polygons, the calculation of the height of the buildings from the ground, and the tessellation of the walls and roofs of the buildings. Pg2b3m tool without the usage of a tessellating tool has been sufficient to generate 3D tile sets from GPR survey meshes as the geometries have already been exported as triangulated polyhedral surfaces.

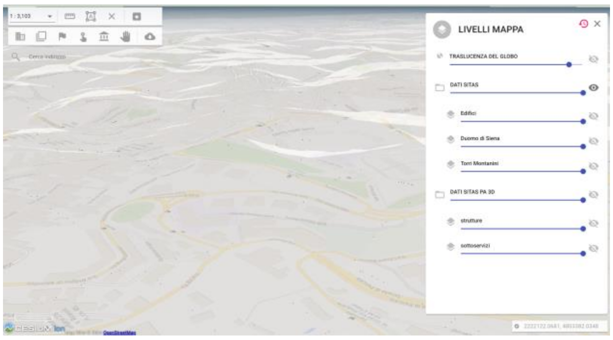

Figure 8: 3D terrain

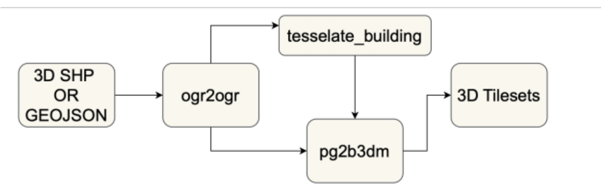

Figure 9: Pipeline for generating batched 3D Tile Model

Another way to generate 3D tilesets is to upload geojson files containing polygons on SITAS’s platform that runs the tool integrated with the Spring Boot framework of the application. The geometries and other attributes are saved to the database and 3D tilesets are created as an underground or archaeological structure.
Finally, .las files are converted to point clouds with the open-source Python py3dtiles library (https://github.com/Oslandia/py3dtiles). The library takes the .las or .xyz file format and converts it to .pnts format enabling many other options to manipulate and modify the input data.

4. CONCLUSIONS

After two years of activity, we can say that a series of results have been achieved and some trends emerge quite clearly. The SoS project in this first phase clearly demonstrated its potential by creating an innovative 3D WEBGIS-based information system, openly sharing collected new and past information about the city of Siena. The implementation of scanning subsurface by GPR required setting up interdisciplinary skills and new protocols clearly demonstrating the concrete possibility of project development and the extraordinary potential of the prospecting method for the knowledge and management of the underground of the city. Furthermore, the pipeline implemented so far also includes and integrates above ground structures offering the possibility to move from traditional approaches, based on data isolation and 2D visualisation, opening new horizons on archaeological research, data analysis and cityscape understanding; the pipeline implemented to develop the 3D viewer has been fully based on open-source tools and is, therefore, freely usable, and replicable in other contexts. Finally, it is worth to emphasise that, similar research projects have been implemented (Haynes *et al.* 2023; Boschi *et al.* 2023; Dabas et al. 2023) or are currently running elsewhere (https://www.yorkarchaeology.co.uk/romanyork).

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