Integrating 3D survey and open datasets for creating low-cost urban digital twins in VR

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Abstract

This paper presents a low-cost framework for creating urban digital twins in Virtual Reality (VR) tailored for heritage preservation and smart city applications. The increasing demand for urban digital twins necessitates an integration of diverse data sources to enhance urban management, particularly in historical contexts where traditional methods may lack necessary specificity. To address this, our research integrates advanced 3D survey techniques (mostly low-cost) with publicly available datasets to develop a semantically rich, detailed urban digital model aligned with specific requirements of each unique urban setting.
The methodology hinges on three pivotal stages: data acquisition, data management, and data accessibility. Data acquisition involves collecting extensive data both from existing datasets and 3D surveys, emphasizing on identifying optimal, cost-effective solutions suited to the surveyed area. Data management is achieved using a broker database coupled with a Web Application Programming Interface (Web API), ensuring the integrity of original databases while enabling flexible system implementation. Data accessibility extends to a broad range of applications, including GIS, BIM, and customized applications, enhancing the scalability of the digital twin model.
The test ground of this system is a VR application developed with Unity, which serves as the interactive platform for the digital twin model. The proposed framework is validated through three case studies in distinct urban settings, each chosen to illustrate the framework's adaptability, versatility, and effectiveness in different urban complexities. The results demonstrate the potential of the digital twin model in facilitating detailed urban management tasks, promoting sustainable heritage conservation, and fostering smarter urban environments.

1. Introduction

Urban management, especially in historic and monumental areas, poses significant challenges due to the need to delicately balance preservation with modern urban dynamics.
The integration of smart city technologies coupled with digital twin systems has been recognized as a key strategy to enhance decision-making, diagnostics, monitoring, maintenance, and safety planning in urban areas (Deng et al., 2021). The global smart city market is projected to grow significantly in the coming years: for instance, according to Next Move Strategy Consulting ("NextMSC," 2024) it was valued at 392.9 billion USD in 2019 and is expected to reach 1380 billion by 2030 with a Compound Annual Growth Rate (CAGR) of more than 12% from 2020 to 2030. As claimed in (Allam and Newman, 2018), citing other studies on the subject, the branding strategies employed by smart city providers may be overly standardized (cit. "one size fits all model"), potentially disregarding the nuances of local economic conditions. In historical/monumental contexts, the challenges represented by very specific and/or detailed applications are stronger: general purpose digital twin systems often fail to address the cultural and historical aspects of the city or the unique requirements of such areas (Angelidou et al., 2017; Angelidou and Stylianidis, 2020), prompting the need for innovative solutions that provide high-fidelity, semantically rich urban representations tailored and customized on very specific features and requirements.
One of the principal challenges is managing data across varying levels of granularity and spatial scale. This encompasses both data pertaining to single buildings or elements of historical or artistic significance, as well as data that describes the broader urban area. This raises two important questions concerning the acquisition and management of data.
Publicly available data providers, like Google Earth ("Google Earth," 2024), Open Street Map ("OpenStreetMap," 2024) and Cesium ("Cesium," 2024) just to name a few, have laid significant groundwork in worldwide digital mapping and data visualization, but they typically offer broad, general-purpose applications/tools rather than detailed, context-specific solutions and lacks the granularity needed for detailed urban planning in specific contexts. On the other hand, available datasets from municipalities and private entities are valuable sources of information enriching geospatial data with semantic and informative content. Nevertheless, they address primarily cartographic purposes and often lack the specificity needed in some contexts. Finally, ad-hoc 3D survey offers the highest level of tailoring acquired data to specific needs, documenting and describing architectural objects as close as possible to the specific requirements a particular application need. However, to provide significant information, they must be properly processed and enriched with semantic content, a task that is generally time-consuming and resource intensive. The most cost-effective solution, therefore, is to integrate existing public and private datasets with low-cost survey data tailored to the representation needs. By combining the broad, foundational data from public sources with the targeted, detailed information obtained from tailored surveys, this approach leverages the strengths of each data source while minimizing costs and maximizing the utility and relevance of the data for specific urban planning and development objectives.
This research introduces a novel low-cost digital twin framework executed in a Virtual Reality environment, aimed at enhancing urban planning processes through advanced information management utilizing integrated low-cost 3D survey and open datasets. Data integration aims to achieve a level of detail and semantic richness that is specifically tailored to the needs of small-scale urban heritage conservation and planning. This targeted approach ensures that the digital twin not only simulates physical reality but also embeds essential context, making it uniquely advantageous for heritage cities. The system allows

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stakeholders — from city planners and conservationists to the public — to explore and interact with contexts in a way not necessarily constrained by high-cost implementation. By doing so, it seeks to democratize technology for urban management, especially in settings that are typically resource constrained.

2. System Framework

The proposed framework is structured around three critical stages, each tailored to address the complexities of integrating and managing urban data: data acquisition, data management and data accessibility.

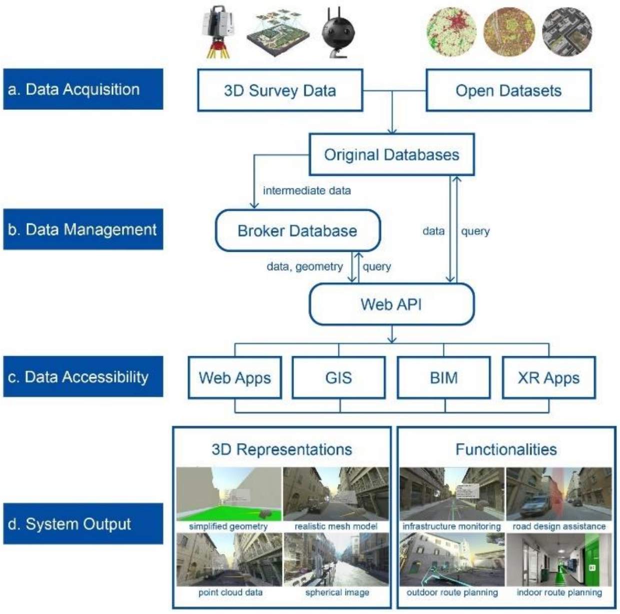

Figure 1. Graphic scheme of the proposed framework.

2.1 Data Acquisition

This stage (Figure 1.a) involves the collection of extensive data from diverse sources, both from existing datasets and ad hoc 3D surveys, with an emphasis on identifying optimal, cost-effective solutions tailored to the specific characteristics of the area being surveyed.

Publicly available datasets from municipalities and private entities (e.g., Open Street Map (OSM), Regional Technical Cartography (CTR)) are valuable tools for accessing data on infrastructure, buildings, terrain, water bodies, administrative boundaries, etc., offering extensive descriptive and textual information associated with the spatial geometry of various features. Such datasets data are generally intended for small-scale representation, making them best suited for general overviews but they often lack in terms of level of detail (LoD) when working at larger scales.

Moreover, their structure cannot be freely modified or integrated with more specific and detailed information needed to thoroughly describe the specific area of investigation. To address this, it is often essential to complement these datasets with additional data and customized field surveys. However, it is important to maintain the integrity of the original data structure to ensure consistency and compatibility.

3D data collection in urban and architectural environments can nowadays rely on the availability of several geomatic techniques, mainly range-based and photogrammetric technologies. Range-based surveys can be conducted using fixed (tripod-mounted) Terrestrial Laser Scanners (TLS) or mobile systems handheld or mounted on vehicles (e.g., SLAM technology). Fixed systems offer high resolution and accuracy but are suitable for small areas/architectural evidence or when high LoD are required. Conversely, mobile systems can be employed in larger areas or to survey exterior or interior paths but are less accurate. Unmanned Aerial Vehicles (UAVs) equipped with LiDAR or imaging sensors can be used to map large areas with a focus on land cover and roof characteristics. When flying at lower altitudes and/or with oblique poses, they can accurately map also street pavements and the upper parts of facades.

Among the photogrammetric techniques, close-range photogrammetry provides detailed geometric data with high accuracy and resolution and is ideal for small, complex areas where detailed measurements are required; spherical/panoramic photogrammetry are rapidly evolving as an effective tool also for long and enclosed paths within building or along urban streets, thanks to their easy portability (e.g. installation on backpacks or on vehicles) and their high-speed capture, being able to detect the surrounding 360° environment with a single shot.

Figure 2 outlines various advanced survey techniques used to create detailed 3D representations of urban and architectural environments, considering different scales, operator requirements, and associated costs (Balado et al., 2025). The selection of a single method or a combination of methods for each project is based on their efficiency in capturing the required level of detail, cost-effectiveness, ease of use, and the specific demands of the project environment. Terrestrial laser scanning, UAV photogrammetry, and spherical photogrammetry are utilized in the case studies of this paper.

	Laser Scanning				Photogrammetry	
	Terrestrial Laser Scanning	Aerial Laser Scanning	Mobile Mapping (Vehicle)	Mobile Mapping (Human)	UAV Photogrammetry	360-Degree Camera
skilled operator	●●○○	●●●●	●●○○	●○○○	●●●●	●●●○
cost	●●●○	●●●●	●●●●	●●●○	●●○○	●●○○
object dimension	Architectural	Urban	Urban	Urban/ Architectural	Urban	Urban/ Architectural
equipment						

Figure 2. 3D survey techniques and their characteristics.

2.2 Data Management

Data management within the system has been designed with the dual aim of preserving the integrity and structure of the various original databases/datasets while also enabling scalable and flexible system implementation and customization. This is achieved through the use of a broker database coupled with a Web Application Programming Interface (Web API), as shown in Figure 1.b, which allows for seamless integration and data harmonization.

2.2.1 Broker Database

The broker database acts as an intermediary layer between the original data sources and the applications. This layer performs several critical functions that are essential for integrating diverse data sources and preparing them for practical use.

The primary function is data integration. Urban projects typically draw on diverse data types that originate from different sources. These can include architectural analysis, preservation status, historical records, 3D survey data, and geographic information. The broker database facilitates the integration of these heterogeneous data types, such as linking point cloud data from 3D surveys with GIS data from OpenStreetMap. This integration capability provides a unified, consistent view of all relevant data, ensuring that disparate information sources work together seamlessly.

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The broker database plays also a pivotal role by allowing the addition of new data attributes that augment the original datasets. Adding further complexity to urban projects is the need to enrich existing datasets with additional attributes that deepen analysis and enhance information utility. This capability is crucial for tailoring the data to meet specific project needs and for ensuring that all relevant information is accessible in a cohesive and integrated manner. Moreover, the broker database supports comprehensive geometry management, allowing additional geometric data to be stored for each object, such as extruded 3D geometries, bounding boxes, segmented point clouds, interactive hotspots, and so on. All these elements enhance visualization/navigation processes or data enrichment. For instance, bounding boxes of geometric entities can be computed and added to the database with the aim of optimizing rendering by displaying only features within a certain distance to the user; extruded 3D geometries from 2D GIS shapes might be required to enable 3D visualization in BIM or XR applications; segmented point clouds allow for detailed analysis and isolation of specific architectural features, essential for data integration in heritage preservation projects; interactive hotspots further enrich the user experience, enabling straight-forward interaction and providing access to additional information and external resources.

Another key function of the broker database involves the conversion of various file formats to unified formats compatible with end-use applications, such as converting E57 and LAZ point cloud data to PLY, or OBJ and 3DS files to FBX. This capability ensures that data from diverse sources can be seamlessly integrated and utilized within the application without compatibility issues.

Lastly (although not in an exhaustive list), the broker database handles transformations necessary to co-register different spatial reference systems (SRS), such as unifying the SRS, applying translations to reduce coordinates, and performing axis shifts (e.g., many general-purpose 3D engines expect the Y axis to be vertical). This is crucial as data sources like BIM, GIS, and survey data may use different coordinates or reference system.

2.2.2 Web Application Programming Interface

The Web API serves as the nerve centre of the data management system, facilitating a wide array of functionalities that enhance the interaction between external applications and the broker database. It provides several controllers, each designed to streamline specific aspects of data management and accessibility:

The *Database Controller* oversees the creation and maintenance of the broker database, efficiently drawing data from various original sources, transforming it as necessary, and integrating it into the broker database. This process is foundational for preserving the integrity of the original databases. The Database Controller also grants external users access to the databases structure and the table schemas, enabling direct interaction with the data architecture. This access empowers users to make informed decisions about data access and utilization.

The *Binary Data Controller* manages the upload of additional attributes to the broker database, including textual descriptions, images, and other multimedia files. It plays a pivotal role in handling large sets of binary data, such as images, 3D models, and other multimedia elements integral to the digital twin environment. This controller enables external users to upload or download these binary files efficiently, ensuring seamless and robust storage and retrieval processes. Moreover, the Binary Data Controller converts diverse data formats into the target formats required by the application, facilitating seamless data integration and use across different platforms and applications.

The *Geometry Controller* handles all transformations related to geometry. For example, it enables users to extrude 2D shapes into 3D geometries based on associated height data, which are then stored in the broker database as binary data in PLY format. Additionally, it computes and stores 3D bounding boxes for objects, which are instrumental in calculating distances between specific coordinates and various 3D objects within the digital twin environment. This capability not only enhances the visualization aspects of the digital twin but also improves spatial analyses and interaction within the virtual environment. Moreover, the geometry controller carries out the calculation for the route planning function. It also manages the conversion of different spatial reference systems to ensure that all geographical data aligns correctly.

The *Query Controller* enables efficient data querying once the data is structured and securely stored within the broker database. It processes application requests, retrieves the required data, and returns it in a readily usable format. Users can create and send custom query strings to the database, receiving results based on these queries. This function is crucial for extracting specific datasets or conducting detailed analyses, enabling tailored data interactions that support a variety of operational requirements.

2.3 Data Accessibility

The Web API enables broad data accessibility, catering to a wide range of applications and user needs (Figure 1.c). For GIS users, it provides both direct access to the original databases for unaltered data and the capability to retrieve integrated information from the broker database (Bruno et al., 2020). For BIM users, the Web API, in conjunction with the broker database, serves as a bridge that connects their systems with external databases. This connection facilitates the enrichment of BIM projects by incorporating additional information, such as detailed material data, decay mapping, or past preservation interventions (Bruno and Roncella, 2019).

Moreover, the system supports data access through various customized applications tailored to specific platforms including mobile, desktop, web, and extended reality (XR) technologies. Among these, XR stands out as the forefront of digital interaction, providing immersive experiences that transform user engagement with data. Particularly, Virtual Reality (VR) technology is instrumental for users requiring spatially accurate, real-time representations of urban environments. This immersive capability is vital for enhancing understanding and facilitating more informed decision-making, making it an invaluable tool in urban projects. Therefore, in this paper it was chosen to validate the functionalities and scalability of the proposed system within a VR environment.

3. VR Application Design

In the current stage of development, a standard template for VR applications focused on urban digital twins is designed with Unity3D (Unity3D, 2024). This template includes essential functions to support effective interaction within urban digital environments. Furthermore, it is designed to be scalable, allowing for the addition of specialized functions and features based on the unique requirements of each urban scenario. This adaptability makes it suitable for diverse urban development projects.

3.1 Configuration and Settings

One of the key components of the Unity template is the ProjectSettings class, designed as a ScriptableObject, that stores essential settings needed to retrieve data from the broker database via the Web API and to facilitate project operation. It encapsulates crucial configurations such as the Web API URL, the definition of the Unity reference system along with the

required coordinate transformation settings, and the schema for geometry tables, along with a query builder. A user-friendly graphical interface in Unity's inspector allows developers to conveniently modify these settings. The data within ProjectSettings is accessible across all scripts, ensuring unified application logic and functionality control.
The SteamVR (“SteamVR,” 2024) package is added to setup the VR environment and enabling basic interactive experiences such as moving within the virtual environment, teleporting to different locations, and laser pointing for UI interactions. The integration of SteamVR for Unity facilitates cross platform compatibility, leveraging its extensive developer tools and efficient development process to enrich the user experience.

3.2 Dynamic 3D Object Importation

The application dynamically loads and visualizes 3D objects within specified proximities to the user, which is achieved through real-time connections to the database via the Web API.
As users navigate the VR environment, the application continuously updates and transmits their transformed world coordinates to the Web API. In response, the API queries the database and retrieves a list of element IDs for 3D objects located within a predetermined distance from the user. These IDs are derived from the geometry tables specified in the ProjectSettings. Once the IDs are received, the Web API facilitates the import of the corresponding binary files, which may include various formats like mesh models or point clouds. These objects are then rendered in the Unity application, providing a visually rich and interactive experience. Each imported 3D object is integrated with a custom script that stores its ID and the name of its corresponding table, which organization supports further interactions and complex data queries.
Additionally, each object is equipped with a mesh collider component, allowing for interactions such as pointing and selecting. For navigational ease, the "teleportation areas" component is automatically added to ground elements like roads and sidewalks. These designated zones enable users to move swiftly across the virtual landscape, teleporting to different locations instantaneously. This feature is essential in large or complex urban environments, where it improves the overall navigability and user experience by allowing quick and efficient exploration.

3.3 Data Query and Display

The query-builder within the ProjectSettings class is designed to facilitate efficient data retrieval. As shown in Figure 3, it queries the broker and the original databases schemas with the Web API’s database controller, which gets the available connections and displays a list of tables from the selected database in the Unity inspector interface. Developers can then view and select from the list of column names presented with checkboxes, enabling them to choose one or more columns for the output. Additionally, developers have the option to link these selections with another table, specifying the logic for the join. This functionality allows for the creation of simple to complex queries, either from a single table or by joining two tables. Once constructed, these queries are stored within the "saved queries" section of the ProjectSettings, making them readily accessible across different scripts.
In the virtual reality environment, interaction with data is made intuitive and user-friendly through the use of VR controllers. These handheld devices enable users to navigate and interact within the virtual space effectively. A Worldspace canvas is attached to the player’s left controller, offering easy access and adjustment by the user. Interaction is facilitated through the right controller; when a user points at a 3D object and triggers the action, the system's laser pointer interacts with the object’s mesh collider. This interaction captures the object’s ID and associated table name, which are then used to formulate a query. The specific ID is added as a condition in one of the pre-saved queries, tailored to meet the functional needs of the particular case. This completed query is subsequently sent to the Web API’s query controller, which retrieves the relevant data from the database.
The fetched data, which may include textual, numeric, pictorial, and binary types, is then dynamically displayed on the canvas. This system ensures that all relevant information related to the selected object is visually presented to the user, facilitating an interactive and informative experience within the VR environment. This method not only enhances user engagement by providing real-time data interaction but also supports detailed analysis directly within the immersive VR setting.

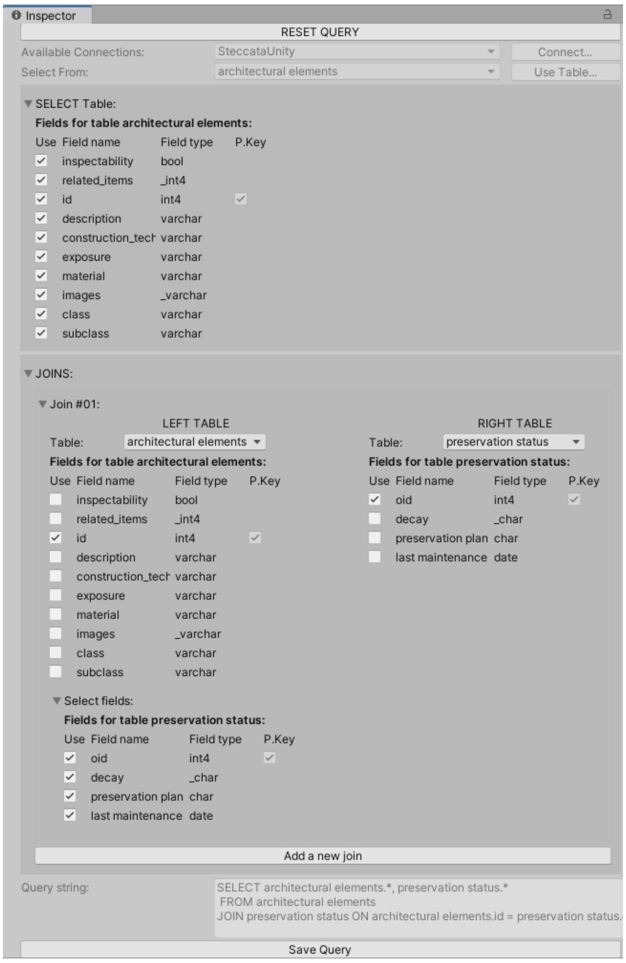

Figure 3. The query-builder GUI in Unity.

3.4 Representation Techniques

As shown in Figure 4, the application allows users to toggle between different visual representations of the 3D environment — point clouds, mesh models, simplified geometry models, and spherical images — each designed to suit varying analytical requirements.
For point cloud visualization, a custom package, “PCX,” is employed to manage point data efficiently. An LoD group enhances this visualization by adjusting the detail level based on object distance, optimizing memory usage and performance without compromising visual quality, essential for maintaining immersion.

For spherical image visualization, the broker database includes a table storing photos with their capture locations. Similar to the 3D objects, the Web API returns a list of IDs for spherical images near the player. Each image is retrieved and used to texture a sphere prefab instantiated at the recorded location. When a player interacts with one of these spheres using his controller, he is transported to a new scene where the spherical image serves as the skybox, creating an immersive panoramic experience.

Figure 4. Four different representation methods in the VR view.

3.5 Spatial Navigation and Route Planning

The VR application is equipped with advanced tools for spatial navigation and route planning, crucial for urban planning and simulation exercises.

3.5.1 Unity's Navigation Tools

One method for route planning within the application utilizes Unity's navigation tools. In the case of pedestrian route planning, walkable areas, such as sidewalks and pedestrian crossings, are downloaded from public data source such as OpenStreetMap and integrated in the broker database. The WebAPI then imported them as 3D objects into Unity. Upon these imported geometries, a navigational mesh, or NavMesh, is constructed. This NavMesh delineates all areas accessible to the user, serving as the foundation for dynamic route calculations.
When a user selects a destination — either from a list of predefined locations such as imported building IDs or by pointing to a desired spot in the VR environment — Unity's navigation system calculates the shortest path from the user's current position to the target. This path is then visually represented as an animated line with flowing arrows, providing a clear and engaging visual guide that helps users follow the route through the virtual city.

3.5.2 PostgreSQL and PostGIS Approach

Alternatively, the application can leverage the capabilities of the broker database (which in this case studies is based on a PostgreSQL ("PostgreSQL," 2024) RDBMS (Relational DataBase Management System) enhanced with PostGIS) for route planning, specifically employing the PgRouting extension. This extension enables advanced routing algorithms to calculate optimal paths across networked data. It does not rely solely on distance, but the optimal route is determined using a cost function that incorporates multiple attributes of the network. This cost function assigns a value to each edge in the network based on these attributes, allowing the routing algorithms to evaluate the trade-offs between different path characteristics.
This method begins similarly to Unity's Navigation Tools, where the user selects a destination. However, instead of processing the route directly within Unity, the destination's ID or coordinates are sent back to the broker database using the Web API. The database, equipped with PostGIS/PgRouting functions, then calculates the best path.
Once calculated, the route is transmitted back to the VR environment and visualized in a manner akin to the Unity-based approach. A key advantage of using PostgreSQL with PostGIS is that it offloads the computational demands from the client-side application to the server, leveraging the database's robust capabilities for spatial analysis and route computation. In addition, PgRouting can identify the best path that balances the user's specific requirements rather than just focusing on distance, ultimately delivering a route that optimizes the desired attributes. This flexibility makes it suitable for various applications, including safety route planning.
Both approaches — Unity's built-in tools and the PostgreSQL/PostGIS integration — provide the application with flexibility and power, catering to different technical preferences and resource availabilities. Users can benefit from a system that not only supports detailed route planning but also adapts to the specific demands of the urban planning scenarios encountered.

4. Case Studies

The utility of the digital twin model is examined in three different case studies, each highlighting different aspects of urban complexity. The case studies demonstrate, also, the system's effectiveness in handling various urban management tasks.

4.1 Case Study 1 – the Steccata Church in Parma

The first case study focuses on Santa Maria della Steccata, a renowned Catholic Marian sanctuary characterized by its Renaissance and Baroque architecture, situated in the heart of Parma (Italy). This site was selected for its historical significance and the unique challenges it presents in terms of architectural preservation. The church requires restoration and conservation work, providing an opportunity to test the system in managing data at an architectural scale.
As for existing datasets, in this specific context, municipal data and regional cartography proved to be useful for obtaining general information about the building, its history, and its surroundings. This information was supplemented with a detailed integrated 3D survey that included laser scans (Leica RTC 360) of both the interior and exterior, close-range photogrammetry (Nikon D3x) of accessible exterior areas up to the first cornice level, and UAV photogrammetry (DJI Mavic Mini) of the exterior and roofs. All survey data was integrated and co-registered based on a topographic survey conducted with a total station and georeferenced through GNSS measurements.
The 3D point cloud was processed to generate a comprehensive mesh model, which was manually segmented to identify and categorize individual architectural elements such as the bronze door and marble reliefs. Each segmented element was then encoded with unique identifiers to bridge the 3D representation and its information stored in the database hosting data about its preservation state and characteristics.
A broker database was established to manage and integrate the diverse data sources. This database houses PLY files representing the simplified 3D geometry of the church surrounding buildings and roads, FBX files for the segmented mesh model, along with metadata detailing the preservation status and descriptive information of each architectural and decorative element.
Currently, the church's front façade is utilized as the primary testing ground for the data query functionality within the VR environment. Key architectural elements on this façade have been equipped with mesh colliders and tagged a custom script (named "Interactable Items"). When a user, via the VR interface,

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points at one of these elements, its controller interacts with the system, sending the element's ID to the Web API. The API then checks whether this ID has corresponding entries in the information and preservation tables within the database.

Based on the results of these queries, interactive buttons related to 'info' and/or 'preservation status' appear on the user's canvas. Users can engage with these buttons through their right-hand controller to select which data they wish to view. Upon selection, the application sends the relevant table name back to the WebAPI, which then constructs a query to fetch all associated data for that object. The data is returned as a JSON string and is subsequently parsed by the Unity application to be displayed on the canvas in an appropriate format, such as text, images in a scrolling view, or dropdown lists, as shown on Figure 5.

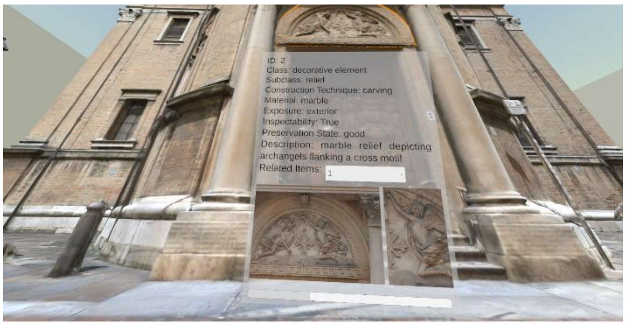

Figure 5. Information query example in the VR view.

4.2 Case Study 2 - Corso Trento e Trieste

The second case study focuses on Corso Trento e Trieste, a 360-meter-long prominent street that begins at Piazza Santa Maria Inter Vineas in the historic city of Ascoli Piceno (Italy). This case study is selected to explore a historic urban setting, emphasizing the interaction between streets and buildings. It also examines the street's dimensional, material, and structural features, along with smart mobility by both pedestrians and vehicles.

In this context, the system was based on data provided by the municipal administration, which included technical drawings of the pavement's stratigraphy and the underground utility network. Additionally, data from OSM layers, specifically the Buildings and Highway categories, was incorporated to enhance the base information. This data was then integrated with 3D surveys conducted through both terrestrial laser scanning and photogrammetry. Laser scans, taken with a Leica RTC 360, enabled the creation of an accurate 3D reconstruction of the road surface and the building facades, providing also the ground truth for supporting the photogrammetric survey. Given the street's narrow and extended layout, the INSTA 360 Pro2 spherical camera mounted on a backpack was used for rapid and on-the-move captures along the entire road. This imagery served both for generating photogrammetric mesh models (Bruno et al., 2024) and extracting orthophotos of facades and pavements, as well as for direct use in visualization or virtual navigation applications.

In the VR simulation, users experience a vivid reconstruction of Corso Trento e Trieste through several visualization methods. Simplified geometry models provide a basic structural outline of the urban landscape, created by extruding 2D polygons from the OpenStreetMap database. These models, stored within the broker database, serve as the initial layer of the digital twin. To add depth and texture, point clouds obtained from terrestrial laser scanning are segmented according to different sections of the street. The database maintains a variety of these clouds, from high resolution dense clouds to 50% and 10% resampled versions, allowing the system to adapt the level of detail based on the user's proximity. This ensures optimal performance and high-quality visuals. Further enhancing the realism, mesh models are automatically generated from the point cloud data, and subsequently segmented (manually) as roads, sidewalks, and buildings. Players can switch between these three different representation methods using the A and B buttons on their right controller. As they move through the virtual space, the Level of Detail (LoD) group component intelligently selects the appropriate point cloud model based on distance, ensuring optimal frame rates and immersive, high-resolution visuals.

Spherical images add another layer of immersion. Stored in a specific table within the broker database, these images are strategically loaded as sphere objects at their exact capture locations as users navigate the virtual scene. Users can enter these panoramic scenes, moving seamlessly between them using the VR controllers, thus experiencing the street from multiple vantage points. Simplified geometry models play a crucial role beyond basic visual representation; they function as invisible mesh colliders that facilitate interaction with 3D objects across different visualization methods. This setup ensures that regardless of how the environment is rendered — whether through point clouds, mesh models, or spherical images — the user can interact consistently with the virtual space. When the laser pointer from the player's right controller hits one of these colliders, it initiates the construction of a query that is then sent to the broker database via the Web API. This query is designed to fetch specific data related to the object in question. For instance, if a player points at a sidewalk, the system retrieves and displays information about the pavement materials. Similarly, pointing at a building could bring up details about its ownership and historical significance, while targeting a street section might reveal data on accessibility features. This information is displayed on a WorldSpaceCanvas, either be attached directly to the controller for ease of viewing or positioned at a fixed spot about 1.5 meters high next to the object itself, ensuring that the information is both accessible and contextually integrated into the user's field of view. The route planning function is enabled with Unity's navigation tools, as previously elaborated. This system, which incorporates walkable areas sourced from OpenStreetMap and integrated into the broker database, enables dynamic route calculations. Users can select destinations and navigate through the virtual model of the street efficiently, guided by visually engaging paths marked with flowing arrows as shown in Figure 6. This integration exemplifies the practical application of digital twin technology in enhancing user interaction within a historic urban setting.

Figure 6. Route planning example in the VR view.

A road design assistance function for the automatic computation of visibility triangles is integrated to facilitate urban planning in this case study. Visibility triangles are crucial elements in road design, especially at intersections and driveways. These triangular zones, defined by sight lines, ensure that drivers have an unobstructed view to detect approaching traffic, pedestrians, and other potential hazards. In general, visibility triangles are established based on the distance a driver can see along the road from a specific point, to stop safely if necessary. By ensuring adequate visibility for drivers, pedestrians, and cyclists, these triangles play a crucial role in creating safer and more efficient roadways.

The size and shape of these triangles can vary depending on several factors, including the speed limit of the road, the type of intersection, and the surrounding terrain or obstacles (like trees, buildings, or signage) that could obstruct visibility.

For each intersection along the street, the WebAPI retrieves the specific details for the visibility triangle computation from the broker database. This data is then transmitted to Unity where the application processes it to calculate departure visibility triangles. As shown in Figure 7, these sight triangles are visualized within the virtual environment as translucent red cones, providing a clear and practical visual aid for urban planners. This visualization allows planners to effectively assess and verify the placement of objects such as parking slots, urban furniture, or other infrastructures within these critical areas. If any objects are found within the sight triangles that could potentially obstruct visibility, they can be identified for removal or repositioning, ensuring safer and more efficient urban road design.

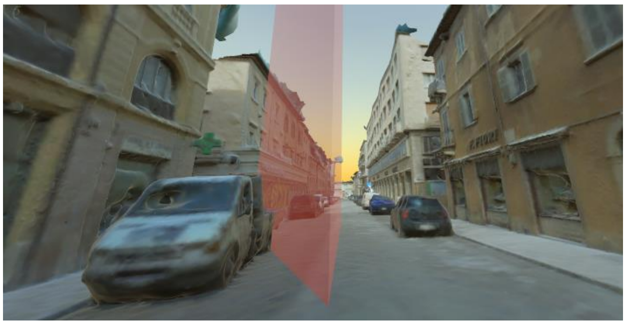

Figure 7. A visibility triangle example in the VR view.

4.3 Case Study 3 – University of Parma Campus

The third pilot site is the University of Parma campus (Italy). It was selected since it functions as an autonomous urban centre, with numerous buildings connected by complex vehicular and pedestrian routes, as well as green spaces and various facilities. It handles substantial traffic during academic sessions, accommodating thousands of visitors daily. In this project, the goal was to create an information system to support campus facility management, with a particular focus on the management, maintenance, and design of pedestrian pathways both within and around buildings. Special consideration was given to ensuring these pathways are accessible and supportive for individuals with limited mobility.

For data collection on the campus structure and individual buildings, technical drawings held by the University of Parma's technical office were used, along with existing orthophotos from prior photogrammetric surveys. The road network was generated through an integrated approach, combining open databases provided by the municipal administration and OSM layers.

This data was supplemented with targeted 3D surveys to increase detail where necessary or to update information reflecting recent changes. These additional surveys included UAV photogrammetry, spherical photogrammetry (Figure 8) – with an approach similar to the one used in Ascoli Piceno - for efficiently capturing data along both interior and exterior pathways, and terrestrial laser scanning.

Figure 8. A 3D view of the photogrammetric survey in a portion of the campus.

A broker database was created to store the bounding boxes and extruded geometry for various campus features including buildings, pedestrian paths, roads, green areas, sports facilities, and parking areas. These features are visualized in Unity, each represented by different colours as illustrated in Figure 9. For the data content, information was stored on vehicle occupancy rates and turnover in parking areas, along with identifying and descriptive details of buildings. Pathway data was also included, focusing on materials, dimensions, and key accessibility factors (such as slope, maximum elevation changes, traction, slipperiness, and the presence of obstacles), as well as the current maintenance and preservation status.

The VR application allows users to virtually navigate the pathways connecting different campus buildings, parking areas, and bus stops. Routes are color-coded to reflect the accessibility attributes of each path. Additionally, a methodology is being developed using the PgRouting extension to identify the most accessible routes between points of interest, leveraging the detailed data associated with each pathway.

Figure 9. A planar view of the campus case study.

5. Conclusion

The application of the developed digital twin framework across diverse case studies not only demonstrates the effectiveness of the proposed methods but also confirms their applicability across a variety of urban contexts. Through these case studies, the versatility of the digital twin model is proven, showcasing its potential to enhance urban planning and management in a range of settings. The combination of the broker database and the Web Application Programming Interface (Web API) approach has proven fundamental to the system's operation, providing a robust and scalable infrastructure that facilitates seamless data integration and management across diverse urban environments. However, the deployment of such comprehensive digital twin systems is not without challenges, which provide valuable directions for future work.

One of the significant challenges encountered involves the management of large 3D datasets, which can be cumbersome to download and integrate into the VR application due to their size and complexity. Future improvements could focus on optimizing data processing algorithms and enhancing the efficiency of data streaming technologies to facilitate smoother and faster integration of these large datasets into the application.

Integrating data from existing BIM projects into the VR application poses another challenge, primarily due to differences in data structuring and formatting. Going forward, developing more robust interoperability standards and tools that can seamlessly translate and integrate BIM data into the digital twin framework will be crucial. This will ensure that valuable architectural and infrastructural data from BIM can be utilized effectively within the VR environment.

Furthermore, incorporating Mixed Reality (MR) technology could significantly enhance onsite cultural heritage preservation activities. By overlaying digital information directly onto the physical environment, MR can provide conservation experts and city planners with real-time, actionable insights. Future work could explore the development of MR applications that are directly linked to the digital twin system, enhancing both the understanding and preservation of cultural heritage sites.

Additionally, allowing users to upload information directly to the broker database, such as future preservation plans or user-generated observations, could greatly enhance the collaborative and interactive capabilities of the digital twin. Developing secure and user-friendly interfaces for data input and ensuring the reliability of user-contributed data will be essential to this expansion.

These future directions not only aim to address existing limitations but also seek to broaden the capabilities of our framework. By advancing these areas, we aim to create a more comprehensive, accessible, and user-centric system that transforms how data is managed and utilized across urban planning and heritage conservation projects, thereby enhancing decision-making and engagement in urban management.

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