Integrated Geomatic Solutions for the Digital Twin of Florence: Protecting the Arno River and its Historic Urban Landscape from Climate Risks

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GSW 2025

Keywords: Urban Digital Twin, River Digital Twin, Data Integration, Monitoring, Cultural Heritage

Abstract

The interplay between urban environments and waterways is a critical aspect of sustainable city planning, particularly in historic settings vulnerable to climate change. This study presents the Digital City & River Twin (DiC&RT) framework, focusing on the historic urban fabric of Florence and its interaction with the Arno River. Unlike conventional Urban Digital Twins (UDTs), which often address isolated domains, DiC&RT intends to analyse the complex relationship between the river and the historic city by means of integrated geomatic techniques. The project addresses flood risks, structural stability, and environmental dynamics by creating a comprehensive multi-layered model. DiC&RT employs diverse data acquisition techniques, including static and kinematic LiDAR scanning, unmanned aerial and surface vehicles for photogrammetry and bathymetry, and ground-penetrating radar for subsurface analysis. A geodetic control network ensures high-precision data integration, supporting long-term monitoring. The study assesses the effectiveness of these methods in capturing the geometric and environmental characteristics of the riverbanks, bridges, and urban infrastructure. The results demonstrate the necessity of combining multiple surveying technologies to obtain a holistic representation of the study area. By integrating spatial and predictive modeling, DiC&RT enables real-time risk assessment and scenario simulations for climate change adaptation. This framework offers a scalable solution for heritage conservation, risk analysis, and adaptive urban management, potentially serving as a model for other historic cities facing similar challenges.

1. Introduction

1.1 Rivers and cities facing climate change

The shape of cities and the rivers that flow through them is the result of mutual adaptation developed over time (Mishra & Saxena, 2024). Bridges, roads and urban areas have been shaped by river features, while human activity has modified the course of rivers with canals and weirs.

Anthropogenic and natural hazards, together with climate change, have placed urban areas at the centre of the European and international political agenda, as evidenced by the Pact of Amsterdam (European Union, 2016) and the UN Habitat III Conference (United Nations, 2016).

In this context, the need for more resilient, inclusive and sustainable cities is among the Sustainable Development Goals (SDGs) of the 2030 Agenda (United Nations, 2015), which promotes urgent measures to reduce environmental impacts, combat climate change and protect cultural heritage. In 2021, the European Commission recommended the digitisation of cultural heritage at risk by 2030, emphasising the importance of advanced technologies for the monitoring and preventive management of properties (European Commission, 2021).

In 2022, the document "Strengthening Cultural Heritage Resilience for Climate Change" (European Commission, 2022) highlighted the role of cultural heritage in the European Green Deal (European Commission, 2019) and proposed good practices for risk management and adaptation to climate change. Current literature recommends a holistic and multidisciplinary approach, with resilient solutions adapted to specific contexts (Khirfan et al., 2020), the use of innovative technologies (IoT sensors, 3D digitisation, machine learning, artificial intelligence) for monitoring and data collection, and a downscaling approach that analyses risk from the regional to the urban level, down to individual buildings (Parente & Ottoni, 2023; Bonfanti et al., 2021; Sesana et al., 2020).

1.2 Digital twins for rivers and cities

In this context, the use of Digital Twins (DT) is emerging for the study of cities (Mazzetto, 2024), historic centres (Castelli et al., 2022) and rivers (Garcia Andarcia et al., 2024). An increasing number of cities are adopting Urban Digital Twins (UDT) for the management of essential resources and services such as transport, energy and water (Ferré-Bigorra, 2022). Significant examples include Helsinki (Hämäläinen, 2020), Rennes (Ketzler et al., 2020), Zurich (Schrotter & Hürzeler, 2020), Boston (Testolina et al., 2024) and Milan (Franzini et al., 2024). However, most current UDTs concentrate on specific domains, including mobility, waste disposal, air quality and infrastructure maintenance, as opposed to an integrated urban management vision. Historic centres, the embodiment of traditional urban culture, are particularly vulnerable: they are urban aggregates of high historical, artistic and environmental value, shaped by historical stratifications and changes in use linked to demographic changes. In such particular contexts, the preventive and restorative measures employed for contemporary cities are not universally applicable; rather, they must be adapted to suit the specific characteristics of each city. With regard to the watercourse domain, the proposed digital twins are intended for the management of water resources. The scale of interest is territorial, generally extending to the entire river basin, while less attention is paid to the interaction between river and historic city.

1.3 Florence and Arno river

An emblematic example is the connection between Florence and Arno river (Lubello et al., 2024; Cantini & Bruttini, 2015). The documented floods, particularly that of 1966 (Caporali et al., 2005), underscore a persistent risk that, while mitigable, cannot

be entirely eliminated. In 1982, UNESCO included the historic centre of Florence in its World Heritage List. Among the elements that contribute to its uniqueness, in addition to the artistic and architectural heritage, is the Arno as a primary element of the landscape context. Since 1966, the shape of the city and the river has seemingly remained unchanged, especially in the historic centre where urban change is constrained by town planning regulations and heritage restrictions. However, the economic and social fabric has changed. While the buildings in the centre were once predominantly residential, the Florentine economy is now based on commerce and tourism. Many properties are now dedicated to the hospitality industry, increasing the perception of overtourism (Tarsi & Carta, 2020).
Changes in the economy and population distribution have altered the use of the river and water resources. As a result, a flood of the same magnitude as the one that occurred almost 60 years ago would have unpredictable consequences today.
Despite the extensive research conducted during this period (Federici et al., 2019, Peruzzi et al., 2019), more detailed knowledge and monitoring of the riverbed geometry, the dynamics of flood events, and the interactions between the river and bridges, buildings, and other urban infrastructures are needed. Furthermore, in light of the rising frequency of extreme weather events, including high-intensity rainfall in concentrated areas over brief periods, there is a need for tools to assist with risk analysis and to predict and monitor the impact on the system comprising the river, its banks, and the surrounding urban area.

1.4 Digital City & River Twin

In comparison to the above-mentioned DTs, the present project is characterised by the objective of studying the interaction of information related to each domain and the realisation of a Digital City & River Twin (DiC&RT) for the investigation of the most significant section of the Arno riverine system within the historic city centre and the adjacent areas.
DiC&RT project involves the creation of a model for analysing and monitoring of the movements of the riverbed following seasonal floods, as well as their interactions with banks, embankments, bridges and other hydraulic infrastructures. It also involves analysing the different scenarios in which the river interacts with the urban and architectural environment, the impact on urban infrastructure and architecture, and the risks to the built heritage and the population from environmental and man-made threats.
Planned activities include:
1. The identification of critical issues and physical and environmental parameters relevant for monitoring the interaction between the river and the built heritage of the historic centre.
2. The retrieval and collection of data from land registry and historical archives, meteorological data and climatic events (such as past floods), urban and tourism statistics from local and national authorities.
3. The creation of geometric, environmental and predictive data layers to accurately represent the current state.
4. The design and deployment of methods and protocols for monitoring changes (e.g. ground surveys, remote sensing, IoT sensors) in critical phenomena (i.e. population density and flows).
5. The geo-referencing, standardisation and archiving of spatial and non-spatial data.
6. The development of predictive analysis tools in risk scenarios to simulate the impact of critical phenomena (river floods, overtourism, ...) and to report and visualise river dynamics, risks and mitigation strategies.
The expected results include:
• An operational digital model of the Arno River for the historic centre of Florence.
• Insights into the interaction dynamics between the river, urban infrastructure and historical landmarks (e.g. bridges, monuments and other relevant artefacts).
• A framework for proactive decision making in risk management and conservation strategy planning.
• The outline of a roadmap for extending the project to other similar contexts.

1.5 Aim a structure of the paper

The aim of this paper is to present the current phase of creating the geometric model and in particular of the present state of a test area. The paper sets out to identify the most efficient workflows by presenting and comparing the results obtained with different tools and techniques.
The objective of the current phase is to identify the most efficient technologies to:
- create the geometric model of the current state,
- update the model,
- monitor significant changes over time.

The study area is defined as the segment of river between Ponte alle Grazie and Ponte Santa Trinita, which encompasses Ponte Vecchio, the oldest and most renowned bridge in Florence. A multi-sensor and multi-resolution approach was used to examine many technologies and instruments with a view to identifying the most suitable ones for each part (riverbed, banks, roads, buildings, infrastructures, facilities, and so on) and in each of the aforementioned phases. Section 2 outlines the technologies and instruments employed, while Section 3 presents the resulting data, which is then discussed in Section 4.

2. Technologies and instruments

The construction of a high-resolution DT requires the use of geomatic techniques capable of acquiring large amounts of data in a short time. To meet the requirements of this study, various geomatic techniques were tested, including geodetic surveys, static and dynamic scanning, photogrammetry using unmanned aerial vehicles (UAVs), bathymetry with unmanned surface vehicles (USVs), and ground-penetrating radar (GPR). The objective was to identify the most appropriate method to ensure high accuracy and rapid data collection while enabling comprehensive and detailed coverage of the study area.

2.1 Geodetic control network

As a preliminary and crucial step, the entire area was framed by a high-precision geodetic network to ensure the reliability of the project. This method addresses the need to achieve geometric accuracies of a few centimetres or less, typical of large-scale surveys of small areas of land for engineering purposes.
Such a level of accuracy can only be achieved through specific topographic procedures, where the geodetic network is a fundamental support for all subsequent determinations.
The geodetic control network, with permanent survey marks placed on the structures along the river, not only ensures the sustainability of the survey over time but also provides a stable and reliable basis for future monitoring activities and data collection campaigns (Jitta, et al. 2025). Although accuracy may

undergo slight and continuous degradation, it is essential to ensure that the final uncertainty does not exceed the expected values. In this context, relative precision between points in the network, which is essential for preserving the geometries of the objects to be surveyed, is particularly important, as opposed to absolute precision, which is often limited to the location of the survey on existing maps. This approach ensures long-term consistency and quality of measurements, while also promoting sustainability by guaranteeing that the survey can meet the operational and environmental needs of future activities.
Strict topographic procedures were therefore adopted to ensure that the entire survey achieved geometric accuracy values in the order of a few centimetres. Specifically, four points of a larger control network, established in the centre of Florence, were surveyed using two Trimble R10 and R12 GNSS receivers[1] and defined in relation to the permanent station IGM2 of the Istituto Geografico Militare (the national mapping agency), located approximately 4 km from the work area. This allowed the points to be included in the official national reference system ETRS89 in the ETRF2000 implementation. The adoption of such a reference system is a fundamental step towards ensuring the uniformity and accuracy of geodetic data at national level, thus promoting consistency between different spatial applications and analyses (Istituto Geografico Militare, 2022).
The next stage involved surveying a densification network. This is a necessary step to set up points of known coordinates in suitable positions to measure the targets used for the detailed survey. The network consists of 20 vertices, arranged as shown in Figure 1 and measured by means of three closed control networks with a Leica TCR-1202 total station. This has resulted in the plano-altimetric definition (with geoid elevation) of all the points in the official national Geodetic Reference System ETRF2000, with relative mean square errors of the order of a centimetre, which is certainly suitable for providing adequate support for detailed surveys.

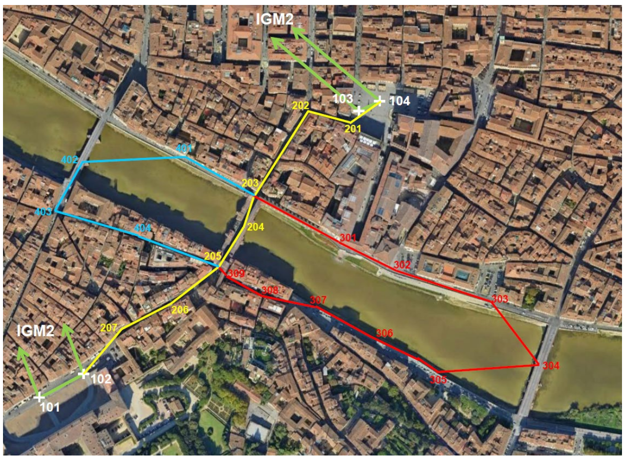

Figure 1. Diagram of the geodetic control network. The main network points (in white) are defined in relation to the GNSS permanent station IGM2 (in green). The densification networks are shown in yellow, red and blue.

All the network points have been materialised by means of metal marks that are firmly fixed to the ground or to the structures using epoxy glue. A comprehensive record was produced for each survey point, including a description of the marker and general and detailed photographs, together with the measured plane coordinates, to facilitate future point location and ensure sustainable management of the survey over time.

[1] https://geospatial.trimble.com/en/products/hardware/trimble-r12

A total of 25 targets were placed on the inner parts of the riverbanks and bridges for the registration and georeferencing data obtained with the various survey instruments used. Targets were measured from the vertices of the densification control network. Where feasible, the same target was repeatedly collimated from different fixed points, and the differences were consistently within a few centimetres.
The coordinates of the targets were used for orientation, georeferencing and validation of the data obtained with different instruments and techniques.

2.2 Laser Scanning and SLAM Technologies

To address the challenges posed by the complexity of the urban and riverine landscape—characterized in this case not only by difficult-to-reach areas such as the riverbanks but also by congested urban environments like those around Ponte Vecchio and the Uffizi—various laser scanners with specific features were employed to assess their effectiveness in meeting acquisition needs under these particular conditions. Specifically, the Riegl VZ-600i laser scanner[2], the XGRIDS Lixel L2 portable LiDAR[3] and the NavVis VLX 3 wearable laser scanner were used[4].
Riegl VZ-600i is one of the fastest laser scanners on the market (with a scan time of 30 seconds for a resolution of 6 mm at a distance of 10 m) and has a range of up to 1000 m (Stampfer, 2024). Full Waveform analysis allows the detection of multiple targets, which is useful for measuring through vegetation along the riverbanks. The instrument has been used both in static mode for ground-based acquisitions and in kinematic mode along the river using a boat. This enabled the acquisition of the intrados of the bridge arches and all areas that would have otherwise been inaccessible through ground-based survey alone.
A total of 118 static scans were carried out along the riverbanks, adjacent streets, and Ponte Vecchio. Scans were processed using Riscan Pro software (RIEGL Laser Measurement Systems, 2024), georeferenced to the target coordinates obtained from the topographic survey, and registered using the Multi-Station Adjustment algorithm. The resulting point cloud consists of 2 billion points (1.9 billion after noise point filtering).
With the Kinematic App, Riegl VZ-i series terrestrial 3D laser scanners can seamlessly switch from static to kinematic data acquisition. This enabled the laser scanner to be placed on a boat to collect data while moving along the river, ensuring comprehensive coverage of the areas of interest. In this mode, trajectory data acquisition can only begin if GNSS correction data is available and the RTK correction of the scanner's integrated antenna is fixed. Once initiated, kinematic scanning can be performed using two different methods:
• Kinematic rotating frame scan (Radar mode): During data acquisition, the scanner continuously rotates.
• Kinematic fixed frame angle scan (Fix mode): The scanner operates in a linear scanning mode, maintaining a fixed angle.
In both cases, after initiating trajectory acquisition, a static scan was performed at the beginning and end of the route to improve post-processing results.
During kinematic data acquisition, it is crucial to keep the platform (in this case, a motorboat) moving at a constant speed. The recommended maximum speed for the rotating frame scan is 10 km/h, while for the fixed frame angle scan mode, the maximum speed is 15 km/h.

[2] http://www.riegl.com/
[3] https://xgrids.com/
[4] https://www.navvis.com/

Data processing was carried out using Riscan Pro software, leveraging the georeferencing of the point cloud acquired in static mode. The two kinematic point clouds were then aligned to the static cloud using a cloud-to-cloud registration procedure.

The point cloud obtained from the kinematic rotating frame scan mode is more complete, thanks to the continuous rotation of the scanner during data acquisition, which ensures homogeneous and detailed coverage of the area, with a total of 328 million points that are not colorized, but based solely on the reflectance index. While this mode offers a more comprehensive view, it can result in a higher presence of noise, such as unwanted reflections or inaccurate measurements, caused by the dynamic movement.

Figure 2. An overall view of the photogrammetric point cloud model.

In contrast, the cloud obtained from the kinematic fixed frame angle scan mode is cleaner, with 504 million points (colored due to photogrammetric data acquired by drone). However, it features some shadowed areas, such as the extrados of the bridge arches and parts of the pilasters, where the fixed angle of the scanner does not allow data acquisition.

To evaluate additional SLAM technologies, the same kinematic surveys from both the boat and the ground were conducted using the wearable laser scanner NavVis VLX 3. The acquired data, georeferenced through the topographic network, was processed on the NavVis IVION cloud platform, resulting in a color point cloud consisting of 770 million points.

Additionally, the portable LiDAR XGRIDS Lixel L2 was employed. This device enables real-time modeling and three-dimensional rendering of the real world using 3D Gaussian Splatting (3DGS) method (Dalal et al., 2024). This allows for the creation of a detailed and high-resolution 3D representation of an object from any angle, even when starting from incomplete data. This makes it an ideal technique for updating the model over time, adding annotations directly onto the 3D representation, and facilitating real-time interaction with the DT.

Beyond these functionalities, XGRIDS Lixel L2 also enables the acquisition of highly detailed metric data, making it a suitable tool for precision surveys. Therefore, to assess both the qualitative and quantitative aspects of the acquired data, geometric information was extracted without initial topographic georeferencing. Instead, alignment was performed using a cloud-to-cloud alignment, generating a point cloud consisting of 406 million points.

2.3 Bathymetric, Drone, and GPR Surveys

The bathymetric survey of the riverbed was carried out in two phases using two different sensors mounted on the CHCNAV Apache 4 USV[5].

In the first phase, the CHCNAV D270 single-beam echosounder[6] was installed, with an incidence angle of 6.5° ± 1°, allowing for depth measurements of the riverbed at regular one-meter intervals. Subsequently, to achieve a more detailed mapping, the CHCNAV HQ-400 multibeam sonar system[7] was employed, featuring an incidence angle of 130°. The collected data, influenced by currents and turbulence, is still being processed.

This second system will enable the acquisition of submerged geometries of the Ponte Vecchio piers, providing a more comprehensive and accurate representation. These surveys will also be crucial for comparison with bathymetric data collected in 2016 as part of the *"Progetto Firenze 2016"* (Federici et al., 2019; Peruzzi et al., 2019; Aminti et al., 2020; Aminti et al., 2022). Launched in 2014, this project aimed to fill knowledge gaps in monitoring the urban stretch of the Arno River on the occasion of the fiftieth anniversary of the 1966 flood. The comparative analysis between the newly acquired data and past data will allow for the assessment of potential morphological changes in the riverbed over time.

Using the DJI Mavic 3 Enterprise drone series, over 2,600 photographs were taken to integrate data related to the rooftops of buildings along the riverbanks. Data processing with 3DF Zephyr software (3Dflow, 2024) generated a dense point cloud consisting of 18 million points (Figure 2).

Finally, thanks to the PROCEQ GS8000 ground-penetrating radar[8], developed by the Swiss company Screening Eagle Technologies, it was possible to acquire data on underground infrastructures and substructures along adjacent roads, beneath

[5] https://chcnav.com/product-detail/apache4-usv
[6] https://geospatial.chcnav.com/products/chcnav-D270
[7] https://geospatial.chcnav.com/products/chcnav-HQ-400
[8] https://www.screeningeagle.com/it/products/proceq-gs8000

the Vasari Corridor, and above the Ponte Vecchio. These data will provide valuable insights into the condition and structural integrity of the subsurface elements, and when integrated into the DT, will support future maintenance and conservation efforts in the historic area.

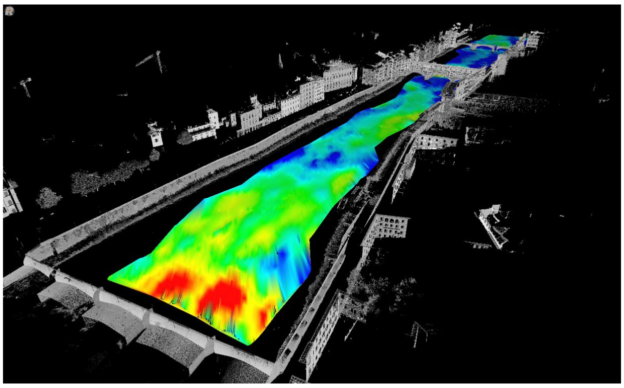

Figure 3. Data integration with single beam bathymetry. The chromatic scale is displayed based on altitude (blue = +84.5 m above sea level; red = +80 m above sea level).

3. Data analysis

The integration of these different technologies enabled the acquisition of a highly detailed and accurate survey in a very short time (the fieldwork was carried out simultaneously by multiple teams over two days), providing essential data for the subsequent phases of the project. The data were analyzed both qualitatively and quantitatively to assess their suitability for the construction of the DiC&RT, evaluate the performance of the different instruments, identify the most suitable acquisition methods for future model updates, and monitor their performance over time.

For the analysis, four sample areas were selected, evenly distributed within the eastern part of the study area, defined both by their location and in relation to the type of surface acquired (Figure 4). Specifically, portions of point clouds were extracted from:

- a riverbank wall on the Oltrarno (South) side (A),
- one of the piers of the central arch of the Ponte Vecchio (B),
- the façade of Palazzo Castellani, which now houses the Museo Galileo and features a rusticated masonry surface (C),
- the façade of a building in the west wing of the Uffizi, covered with plaster (D).

The dimensions of samples A, C, and D were set at 2x2 m², while sample B was slightly smaller, measuring 1.6x2 m², due to the limited area available on the bridge pier, which was reduced in its portion above the water. Each sample area was selected on relatively flat surfaces to ensure a more homogeneous comparison between the data and minimize the influences of complex geometric variations (Figure 5).

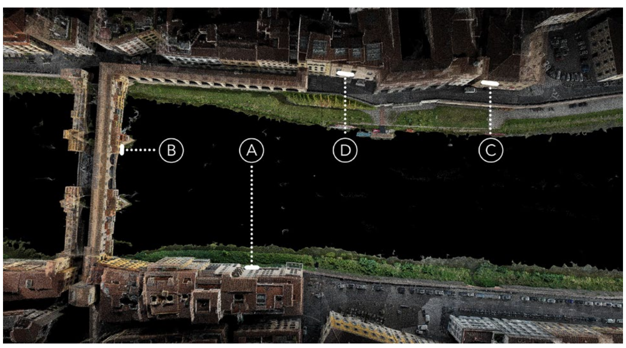

Figure 4. Map of the position of the samples extracted in the eastern part of the study area.

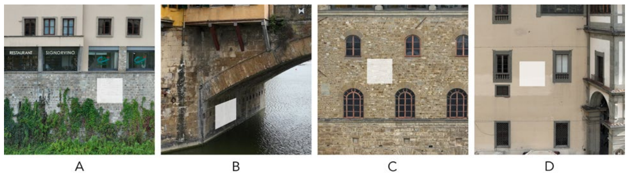

Figure 5. Sample areas for point cloud comparisons (in white).

For each sample, the number of points per square meter (points/m²) was calculated to assess the point cloud density and the quality of the acquired data.

The results obtained with different tools depend on many factors, including the technical specifications of the instrument, the mode and distance of acquisition, the geometry and properties of the materials. One possible approach to comparing the noise of different point clouds is to use a roughness descriptor as a synthetic parameter, especially in a complex real-world scenario. Roughness measures the variation in the geometry of the surface defined by the points, that is, how much it deviates from a smooth or ideal shape. Such irregularity can result from the actual characteristics of the surface, but also from noise or outliers caused by measurement uncertainty and the instrument used. The parameter was estimated using the "geometric features" tool implemented in CloudCompare (Girardeau-Montaut, 2015). This tool computes the distance between a point and the best-fitting plane, which is calculated on the basis of the nearest neighbours. The average roughness was then calculated by setting the local neighborhood radius (i.e., the radius of the imaginary sphere used to define the "local neighborhood" of each point in the cloud) to 0.1 m, in order to account for the different point densities and the geometric characteristics of the point clouds in the different datasets.

Additionally, using data from the static acquisition with the Riegl VZ-600i laser scanner as ground truth, the absolute distances from the reference point cloud were calculated through the Cloud-to-Cloud Absolute Distance (C2C Absolute Distance) algorithm. Tables 1-4 present the mean distance and the standard deviation for each sample. Additionally, in light of misalignments in some areas resulting from successive acquisitions in the same area, the maximum distance is also reported to highlight outliers.

(A)	Riegl stat.	Riegl rad.	Riegl fix	NavVis	XGRIDS	Phgm.
points/m²	4526	7908	25782	2677	4151	232
roughness	0,005	0,003	0,002	0,001	0,015	0,001
mean dist.	-	0,016	0,016	0,110	0,018	0,013
std dev.	-	0,005	0,004	0,005	0,012	0,004
dist. max	-	0,050	0,038	0,134	0,112	0,035

Table 1. Values of the point clouds on the sample of the river embankment wall on the Oltrarno side (Sample A).

(B)	Riegl stat.	Riegl rad.	Riegl fix	NavVis	XGRIDS	Phgm.
points/m²	2366	8365	1577	16058	5171	79
roughness	0,005	0,002	0,002	0,010	0,005	0,002
mean dist.	-	0,013	0,013	0,018	0,032	0,031
std dev.	-	0,026	0,004	0,010	0,020	0,007

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-1463-2025

dist. max	-	0,034	0,051	0,064	0,095	0,064

Table 2. Values of the point clouds on the sample of one of the pillars of the central arch of the Ponte Vecchio (Sample B).

(C)	**Riegl stat.**	**Riegl rad.**	**Riegl fix**	**NavVis**	**XGRIDS**	**Phgm.**
points/m²	11432	4619	10930	4696	7671	86
roughness	0,003	0,003	0,002	0,003	0,012	0,004
mean dist.	-	0,026	0,025	0,163	0,045	0,017
std dev.	-	0,005	0,004	0,020	0,015	0,005
dist. max	-	0,057	0,052	0,255	0,105	0,035

Table 3. Values of the point clouds on the sample of the façade of Palazzo Castellani (Sample C).

(D)	**Riegl Stat.**	**Riegl Rad.**	**Riegl fix**	**NavVis**	**XGRIDS**	**Phgm.**
points/m²	14400	7101	13272	4448	13069	116
roughness	0,002	0,002	0,001	0,012	0,008	0,002
mean dist.	-	0,018	0,017	0,044	0,013	0,040
std dev.	-	0,003	0,002	0,026	0,024	0,008
dist. max	-	0,035	0,035	0,160	0,260	0,063

Table 4. Values of the point clouds on the sample of the façade of the Uffizi (Sample D).

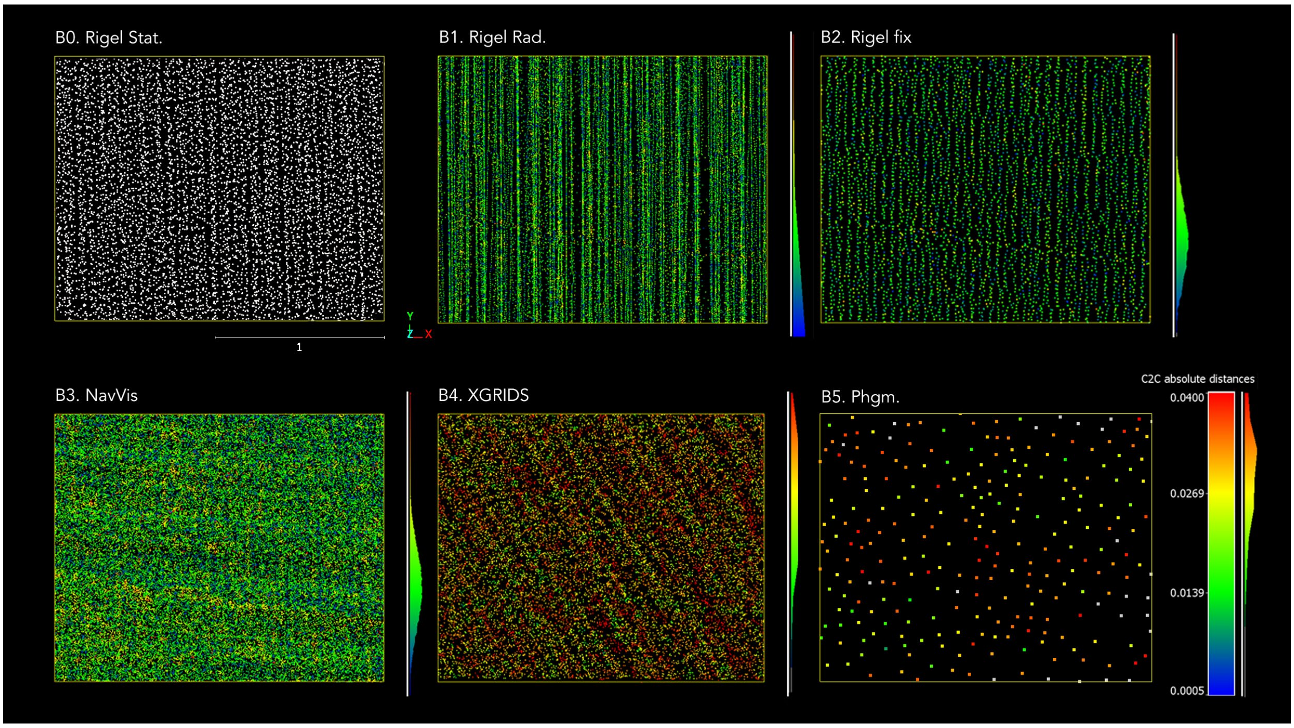

Figure 6. Scalar fields obtained on each point cloud for sample (B) on the pier of the central arch of Ponte Vecchio, compared within an interval from 0,0005 m to 0,04 m.

Figure 6 shows the distance between the reference cloud (static acquisition with the Riegl VZ-600i laser scanner) of sample B (the pier of the central arch of the Ponte Vecchio) and the other clouds. The colour tends to be blue for points closer to the static reference point cloud and red for points further away.

4. Discussion of Results

The results highlight the importance of a multimodal approach to data acquisition for digital twin (DT) construction. While static techniques provide the highest accuracy, the integration of dynamic surveys by water and airborne drones is essential for complete coverage of areas of interest.

The analysis of samples A and B shows that the density of points per square metre is higher in acquisitions with SLAM systems than with static scans, which in this case were performed at a greater distance. This high density allows for significant detail resolution, while the sub-centimetric accuracies confirm the reliability of the technologies employed. However, to ensure the consistency and quality of the final model, special attention must be paid to the workflow to control drift, prevent misalignment and minimise the presence of outliers.

The high-precision control network, combined with correct process metadata, will allow repeat measurements with specific sensors, such as the XGRIDS Lixel L2, used in this first acquisition exclusively for Gaussian splatting visualisation. This will allow further verification and a more targeted selection of the most appropriate sensors for the update phase.

In order to create a reliable geometric reference model that can be monitored and updated over time, a qualitative assessment of the data is also essential. This step ensures the recognisability of artefact characteristics and enables accurate modelling of the urban and river context.

Once the point cloud has been defined to represent the current state, a semantic segmentation is required to define the minimum units of interest with a sufficient granularity to monitor the physical and environmental parameters for the creation of the DT. The modelling will be articulated with different levels of detail (LOD), calibrated according to the characteristics to be monitored over time.

For the definition of the geometric model, in addition to segmentation, it will be necessary to characterise the individual artefacts according to their respective categories (buildings, infrastructure, natural elements, etc.). This process will entail

- the unambiguous identification of each artefact;
- the detailed description through shared vocabularies, specifying type, use and function;
- the documentation of the current consistency;
- the collection and geolocation of past documentation (historical, environmental, etc.).

Once the DT of the test area has been implemented, the replicability of the approach adopted in contexts of interaction between historic cities and rivers with different characteristics will be evaluated, providing insights into the adaptation and application of the developed methodologies.
This extension could support monitoring and risk management strategies in complex environments where understanding changes over time and space is critical to addressing sustainability and resilience challenges. In this way, the model could become a strategic tool for planning in vulnerable areas, facilitating the integration of data from different sources and contributing to more dynamic and informed resource management, while improving responsiveness to changing contexts.

Acknowledgements

The authors thank Microgeo Srl and Dynatech Srl for their consultancy and for providing the instruments, Renzo Maseroli and Donatello Donatelli for their assistance in the topographic network, and Società Canottieri Firenze for their help during the river surveys.
This project is supported by Spoke 7 Project PE 0000020 CHANGES-CUP B53C22004010006, NRP Mission 4 Component 2 Investment 1.3, funded by the European Union–Next Generation EU.
The current paper is part of CHEDAR, project of relevant international interest "Legacy Expo 2020 Dubai" (Interministerial Decree 937 of 4.8.2022), Project of Significant International Interest - Legacy Expo 2020 Dubai, funded by the Ministry of University and Research.
L. Fiorini and A. Meucci research activity is carried out in the framework of the National PhD programme in Heritage Science (La Sapienza University of Rome and University of Florence), A. Conti's research activity is carried out in the framework of the International Doctorate in Civil and Environmental Engineering (University of Florence).

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