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NDT-Driven Digitalization for the Optimization of Inspection and Monitoring Processes of Linear Civil Infrastructures

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In God we trust.
All others must bring data.

Contents

Abstract

The management of transport infrastructure is currently undergoing a paradigm shift, driven by new regulatory frameworks that mandate a transition from reactive maintenance to predictive, data-driven strategies. In this context, this doctoral thesis proposes and implements an integrated workflow for the optimization of inspection and monitoring processes of linear civil infrastructures. Digitalization strategies driven by Non-Destructive Testing (NDT) are analyzed, specifically focusing on the synergistic use of high-performance technologies such as Terrestrial Laser Scanning (TLS) and Unmanned Aerial Systems (UASs) equipped with multi-sensor payloads. The integration process involves the development of a rigorous data fusion methodology that combines geometric precision with radiometric information to enhance defect detection and characterization. These processes are supported by semi-automated segmentation algorithms, implemented in the OPALS (Orientation and Processing of Airborne Laser Scanning data) software framework, which structure massive point clouds into semantic elements. Subsequently, a parametric Scan-to-BIM (Building Information Modeling) workflow is implemented, utilizing adaptive families to convert raw survey data into intelligent digital models capable of serving as dynamic repositories for the infrastructure's lifecycle.

The methodology is tested through two distinct case studies, selected to represent diverse morphological and operational challenges. For Ponte Sisto, the research extends beyond BIM by implementing an immersive Virtual Reality (VR) environment leveraging a real-time rendering engine (Unity), which enables a safe, remote digital inspection workflow. Conversely, the application to the Bridge of Cave addresses the need for standardized data interoperability, demonstrating the effective integration of open-standard models (IFC - Industry Foundation Class) into cloud-based management platforms for continuous monitoring.

Overall, the implementation of these optimized processes designed to leverage BIM and Digital Twins (DT) for the management of transportation infrastructure ensures greater objectivity in safety assessments, improved management of maintenance resources, and enhanced operational efficiency. This research is conducted during a historical period experiencing significant digital transformation in the civil engineering industry. This offers the ideal setting for the proposed methodologies to be

turned into practical applications, advancing the sector towards the realization of a fully functional Digital Twin of the national transportation network.

Chapter 1

Introduction

Transport infrastructure is a basic cornerstone of modern communities, playing a fundamental role in reinforcing economic development, territorial cohesion, as well as social integration. Roads, in particular, have a strategic importance in achieving people and goods mobility, which supports industrial productivity and, further, is crucial for access to basic services. It is within this framework that bridges, viaducts, and engineering structures become key points, which, in terms of safety and efficiency, impact directly on transport infrastructure resilience. It is a fact that, on a European scale, or more specifically in those countries that have a complex geomorphological configuration, as is the case of Italy, the management of road infrastructure has become a key challenge.

The Italian road network is amongst the largest and most complex ones within the European context, with a total length of more than 840,000 km. However, this lengthy network has only a limited extension, with more than 35,000 km, representing about 4% of the total length, consisting of highways and national roads. These corridors host a considerable number of long-span bridges, viaducts, and tunnels. The remaining network length is primarily managed at the local level with almost 80% of the total network managed by the municipal administration and another 16% managed by the provincial, regional, and metropolitan administrations. This level of fragmentation, both with respect to the ownership and management of the infrastructure network, can be considered a typical characteristic of the Italian context.

The complexity of the Italian road network is further accentuated by the dense presence of bridges and viaducts. According to official statistics provided by the national supervisory body [1], there are more than 20,000 bridges and viaducts, more than 2,000 tunnels, and thousands of ancillary structures such as overpasses and underpasses on the motorways and national roads alone. These numbers, which pertain only to the major network, illustrate the size of the portfolio which has to be constantly inspected and cared for. If the total road network, including secondary and local roads, is evaluated, the total number of bridges and other small structures has been estimated to be hundreds of thousands.

A significant portion of this infrastructure was constructed during the rapid economic expansion that followed World War II, particularly between the 1950s and the 1970s. As a result, many structures are now approaching or have exceeded their nominal service life. At the same time, they are subjected to traffic demands, axle loads, and usage patterns that differ substantially from those assumed at the design stage. Environmental exposure, material aging, and cumulative damage processes further contribute to the progressive deterioration of structural performance. In this context, ensuring acceptable safety levels across such a vast and heterogeneous asset stock has emerged as a pressing issue for both technical practitioners and public authorities.

The collapse of the Polcevera Viaduct in Genoa in 2018 marked a turning point in the public and institutional perception of infrastructure safety in Italy, acting as a catalyst for regulatory reforms and renewed attention to monitoring practices. In the aftermath of this event, the need for systematic, objective, and data-driven approaches to infrastructure management became evident. Traditional inspection procedures, often based on visual surveys and qualitative judgments, have shown intrinsic limitations when applied to large-scale networks characterized by thousands of structures and constrained maintenance budgets. Consequently, national and European strategies have increasingly emphasized the adoption of advanced asset management frameworks supported by digital technologies and standardized data models.

In this context in evolution, the existence of geometric, structural, and condition-related data represents an essential prerequisite for any decision-making process. However, the lack of homogeneous and up-to-date data, especially with regard to infrastructures under the responsibility of local administrations, remains a critical issue that currently hinders the application of effective safety management systems. This situation calls for the development of novel methodologies with the potential to efficiently provide high-resolution data and reduce subjectivity in the condition appraisal of infrastructures.

In the past few years, the use of non-destructive surveying methods, such as terrestrial laser scanning, unmanned aerial systems, and the acquisition of multi-sensor data, has shown numerous promise for the monitoring of infrastructure. When used in the environment of digital information, the technology can be used for the creation of a detailed Digital Twin of the existing asset and hence can help in the transition to a Digital Twin of the transportation infrastructure. This can be used for not only the storage of information but also for the assessment of risk.

Against this backdrop, the digitalization of infrastructure inspection procedures is becoming more and more understood as a leverage factor that can improve the safety and sustainability of the Italian road infrastructure. Indeed, by moving away from traditional paper-based and disaggregated procedures and adopting more integrated and data-driven approaches, infrastructure administrators can better manage the size and complexity of existing infrastructure assets and be compliant with modern European guidelines on infrastructure safety and management. The introduction of the "Decree BIM" (Ministerial Decree (MD) 560/2017) [2] and the subsequent "Bridge Guidelines" (MD 578/2020) [3] has made the transition from reactive to preventive maintenance mandatory, identifying digitalization not merely as a technological upgrade, but as an essential requirement for ensuring public safety and infrastructure resilience.

This doctoral research addresses the critical challenges hindering the full digital transition of civil infrastructure management, specifically targeting the lack of automated solutions for large-scale monitoring and the fragmented interoperability that currently limits multi-scale data exchange. This work outlines a transversal methodological approach to explore in which ways it is possible to integrate advanced surveying tools such as Terrestrial Laser Scanning (TLS), as well as Unmanned Aerial Vehicles (UAVs) with multi-sensor packages (LiDAR, Light Detection and Ranging, RGB, Red, Green, Blue and Thermal), with digital management systems. The main point of such work consists in showing how these methods could be employed to pursue any number of engineering purposes that lie well beyond the simple necessity of geometric interpretation, providing instead an improvement to the inspection processes by ensuring their security and objectiveness, as well as building upon these premises a solid information framework to support any type of decision relating to maintenance.

1.1 Background and context

The management of the Italian infrastructure stock is characterized by a high degree of complexity, stemming from both the heterogeneity of the assets and the fragmentation of managing authorities. A significant portion of bridges and viaducts has now exceeded the nominal service life of 50 years. This aging process is non-linear, often accelerating as degradation mechanisms interact with increasing dynamic loads. In response to this critical scenario, the Italian Ministry of Infrastructure and Transport (MIT) issued the "Guidelines for the risk classification and management, safety assessment, and monitoring of existing bridges" [3]. These guidelines represent a fundamental paradigm shift in the Italian infrastructure management landscape.

Moving away from a reactive, emergency-driven logic, this regulatory framework introduces a standardized, preventive strategy based on a multilevel approach. This hierarchical structure is designed to optimize the allocation of limited economic and technical resources by filtering critical issues at a network scale before proceeding to costly, detailed structural verifications (Figure 1.1).

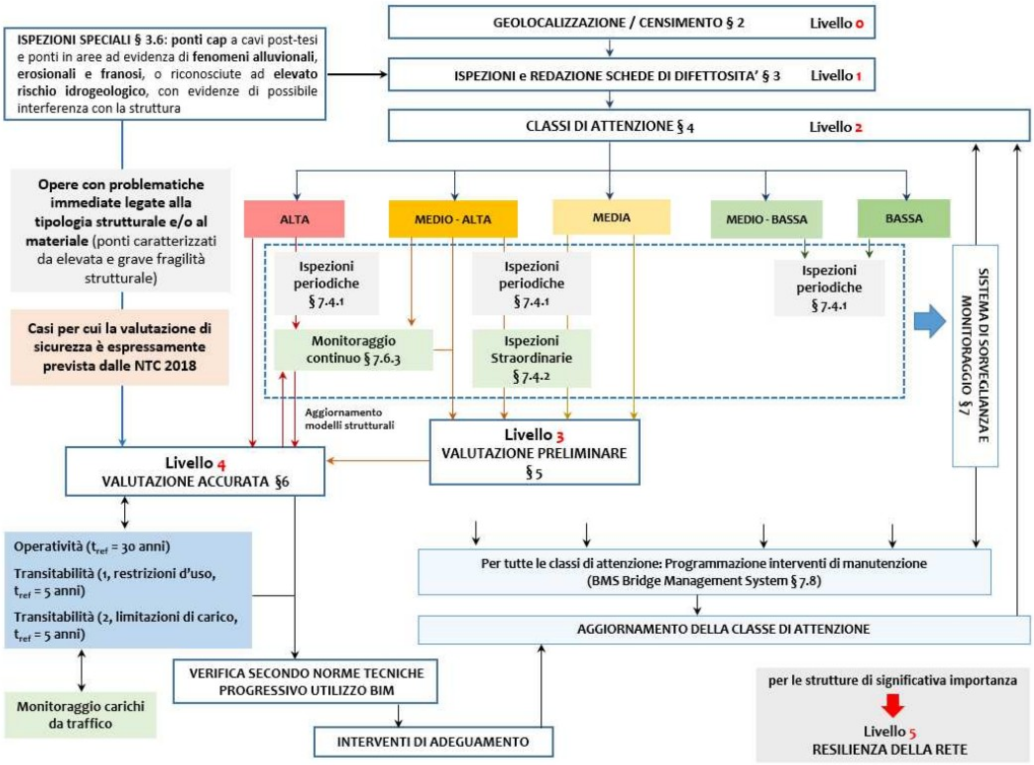


Figure 1.1: Overview of the multilevel strategy for the management of existing bridges [3].

The process begins with a comprehensive census of the infrastructure stock, defined as Level 0, which aims to remedy the frequent lack of historical data and as-built documentation that characterizes much of the existing network. Following this initial inventory, the procedure advances to Level 1, which entails visual inspections aimed at assessing the conservation state of the assets. This phase is critical, as the qualitative data gathered here serves as the primary input for the subsequent risk classification. Based on these findings, the methodology defines a "Class of Attention" (CdA - Classe di Attenzione) at Level 2. The CdA is not a numerical safety factor but rather a risk-based prioritization index derived from the combination of three macro-parameters: hazard (external threats such as seismic or hydraulic risks), vulnerability (intrinsic structural deficiencies and degradation), and exposure (traffic volumes and strategic importance).

The framework acts as a decision-making funnel: only structures classified with a Medium-High or High Class of Attention proceed to more rigorous evaluations. Level 3 involves preliminary assessments to determine if immediate restrictions are necessary, while Level 4 mandates a comprehensive safety assessment compliant with current building codes (NTC 2018 - Norme Tecniche per le Costruzioni [Ministero delle Infrastrutture e dei Trasporti, 2018]), requiring detailed numerical modeling and extensive material testing. Finally, Level 5 considers the broader resilience of the transport network, analyzing the socio-economic impact of a potential bridge failure.

However, the efficacy of this entire decision-making chain is heavily dependent on the reliability of the data acquired during the early stages. Currently, the determination of the Class of Attention is intrinsically sensitive to the subjectivity of the visual inspections performed at Level 1. The interpretation of defect severity can vary significantly between operators, introducing a degree of epistemic uncertainty that propagates through the subsequent risk classification. In this context, the research proposed in this thesis intervenes transversely between Level 1 and Level 2. By integrating Non-Destructive Testing (NDT) and Scan-to-BIM workflows, the objective is to transition from a qualitative, operator-dependent assessment to a quantitative, metric-based diagnosis. This digitalization of the inspection process ensures that the input parameters for the risk algorithms are objective and repeatable, thereby enhancing the reliability of the entire management system.

One of the most critical issues lies in the limited knowledge of the existing infrastructure stock. In many cases, the actual number and distribution of bridges and related structures within a network are not fully known, resulting in a pronounced census gap. Even when assets are formally identified, original design documentation, as-built drawings, and records of past interventions are frequently unavailable or fragmented. As consistently highlighted in European guidelines and international best practices, a reliable and comprehensive inventory constitutes the fundamental prerequisite for any Bridge Management System (BMS); in the absence of such baseline information, subsequent phases of structural assessment and risk analysis are inherently compromised.

The continued reliance on traditional visual inspections leads not only to subjective evaluations, but often results in incomplete, inconsistent, or, in some cases, entirely omitted inspections. The lack of objective and quantitative data prevents the reliable tracking of damage evolution over time, reducing inspection activities to a formal compliance exercise rather than a diagnostic and decision-support tool. This limitation severely constrains the ability to detect early-stage deterioration mechanisms and to implement timely mitigation measures.

Chronic funding constraints force infrastructure operators to function under persistent resource scarcity. As a consequence, the majority of available financial resources are allocated to addressing unforeseen emergencies through corrective maintenance actions, leaving limited capacity for strategic planning and preventive maintenance. This reactive approach hinders the adoption of long-term management strategies based on priority indices and performance indicators, as advocated by contemporary Asset Management (AM) methodologies and life-cycle oriented frameworks.

The combined effect of incomplete data, inadequate inspections, and emergency-driven decision-making inevitably leads to a systematic underestimation of structural and operational risks. Without an objective quantification of the infrastructure's health condition, achievable only through the integration of Non-Destructive Testing (NDT) techniques, assessments of structural and seismic vulnerability remain largely uncertain. This condition exposes the network to latent criticalities that may remain undetected until severe damage or collapse occurs.

Within this context, the digitalization framework proposed in this thesis should not be interpreted as a mere technological upgrade, but rather as a necessary response aimed at disrupting this vicious cycle. By enabling the acquisition, integration, and management of reliable and objective data, the proposed approach supports informed decision-making and facilitates the allocation of resources where they are most critically needed.

To address these challenges, public administrations and managing bodies are increasingly required to implement BMS capable of storing and analyzing data to prioritize interventions effectively. Recent academic and institutional research initiatives have underscored the necessity of creating vector databases and GIS-based catalogues. These platforms must go beyond simple geolocation; they must serve as dynamic repositories for structural information, inspection histories, and risk indices related to hazard, vulnerability, and exposure. Nevertheless, the efficacy of any BMS is intrinsically linked to the quality of the data it contains. Therefore, the transition from static databases to dynamic decision-support tools necessitates the integration of high-frequency, high-fidelity data derived from advanced surveying technologies.

1.2 Importance of infrastructure monitoring and digitalization

Traditionally, the assessment of infrastructure condition relied almost entirely on visual inspections by trained technical personnel. Although these inspections remain an essential ingredient in any safety program, they have presented some inherent challenges and flaws that prevent their effectiveness in asset management practices as well. One of the most significant challenges or flaws with these inspections is their subjectivity in assessment, where, for example, measures of defects in terms of their width or spall area might lean on experience and interpretation by the inspector, with a low repeatability level in their assessment.

Another critical challenge is accessibility, where critical sections such as bridge bearings, underdeck beams, or elevated piers remain hard to access, making inspection processes even more complicated and expensive. Accessing these sections usually demands expensive equipment with limited access, such as under-bridge inspection units (by bridge system). Use of these machines is normally accompanied by high operational and rental costs, as well as safety hazards for inspection team members, particularly when working at higher elevations. Lastly, these inspections usually require either full or partial closure of traffic lanes to accommodate these expensive machines, causing traffic disruptions and incurring indirect economic costs in relation to affected environments or neighboring communities.

Visual assessment reports usually require qualitative description and two-dimensional images, which in most instances lack clear and measured criteria and location, making it challenging, if not complicated, to interpret changes in their condition over time. In all these challenges and flaws, it is vital to note that innovation and use of modern technology in inspection don't aim to eliminate or diminish the importance and role of visual inspection as preliminary assessment or analysis but seek to combine and complement these with accurate and innovative information and approaches to widen and amplify the scope of knowledge on asset condition and outcomes, thereby making detailed and informed decision-making easier and efficient.

To mitigate the disadvantages of the conventional approach, the digitization of the inspection procedure has, thus, become an absolute necessity. Digitalization, in this case, means, and is limited to, the scanning of the paper report contents to digital form and, additionally, is the development of an accurately defined semantic model of the actual structure, known to be the Digital Twin. The digital revolution thus helps facilitate the integration of data, thereby incorporating geometric information related to the structure shape and size, along with the material condition, represented by the data related to defects on the surface of the structure. Digitalization, finally, helps to shift the focus from the concept of corrective to predictive maintenance, scheduled according to the actual progress of the condition of the structure, thus allowing the rational allocation of the budget to optimize safety, the ultimate goal of inspection.

To break free from the constraints of the conventional methods, the digitization of the inspection task is imperative. In the Italian construction industry, the application of technology is no longer a technological evolution. It is actually a mandate in view of the increasingly dynamic Italian regulatory environment. During the last decade, the Italian Ministry of Infrastructure and Transport (MIT) has adopted a series of decrees to digitize the construction industry.

Behind this regulatory evolution is the Ministerial Decree (M.D.) 560/2017, also known as the "BIM Decree" [Ministero delle Infrastrutture e dei Trasporti, 2017]. In this document, the progressive compulsory use of Building Information Modeling (BIM) in building and infrastructure projects was made clear, mandating the adoption of open interoperable formats, like Industry Foundation Classes (IFC). With the BIM Decree, BIM officially entered the public procurement procedures of Italy and offered a plan that considers the digitalization of information, not just in terms of the geometry, but the information management on the whole life cycle.

The need for a nation-wide digital repository was further promoted by the decree M.D. 430/2019, implementing the National Archive of Public Works (AINOP) [Ministero delle Infrastrutture e dei Trasporti, 2019]. The decree aims for a dynamic census of the existing infrastructures, obliging managing authorities to insert data into a common digital repository, covering technical, administrative, and structural aspects. AINOP focuses on the need for interoperability and unique asset identification through the Public Work Identity (IOP), de facto pointing to a Digital Twin concept, in which the physical infrastructure is represented in the nation-wide digital repository and integrated with real-time monitoring data. It is a shift from local archives towards a nation-wide, monitoring-oriented platform.

Recognizing that the majority of the Italian infrastructure stock is aging, the regulatory focus subsequently expanded from new constructions to the management of existing assets. The M.D. 312/2021 updated the previous BIM decree, revising thresholds and deadlines for mandatory implementation and introducing significant amendments regarding the maintenance of existing structures [Ministero delle Infrastrutture e della Mobilità Sostenibili, 2021]. It explicitly encourages the use of digital methods for heritage and existing infrastructure management, introducing reward criteria in public tenders for the adoption of BIM methodologies. This legislative update acknowledges that the digitalization of existing assets, often lacking original documentation, is more complex than new designs, thus requiring specific incentives to bridge the digital gap.

This trajectory culminated with the specific regulations for bridge safety. The M.D. 204/2022, adopting the updated "Guidelines for risk classification and management, safety assessment, and monitoring of existing bridges" [Ministero delle Infrastrutture e della Mobilità Sostenibili, 2022], represents the reference standard for the sector. While M.D. 578/2020 introduced the risk-based multi-level approach, the 2022 update reinforces the role of digitalization in Asset Management. The guidelines explicitly recommend the development of a BIM-oriented digital inventory to support the surveillance and maintenance processes. They highlight that an effective BMS must be fed by accurate, updated, and georeferenced data to support the calculation of the "Class of Attention" and the planning of interventions.

The evolution of this legislative framework is summarized in Figure 1.2.

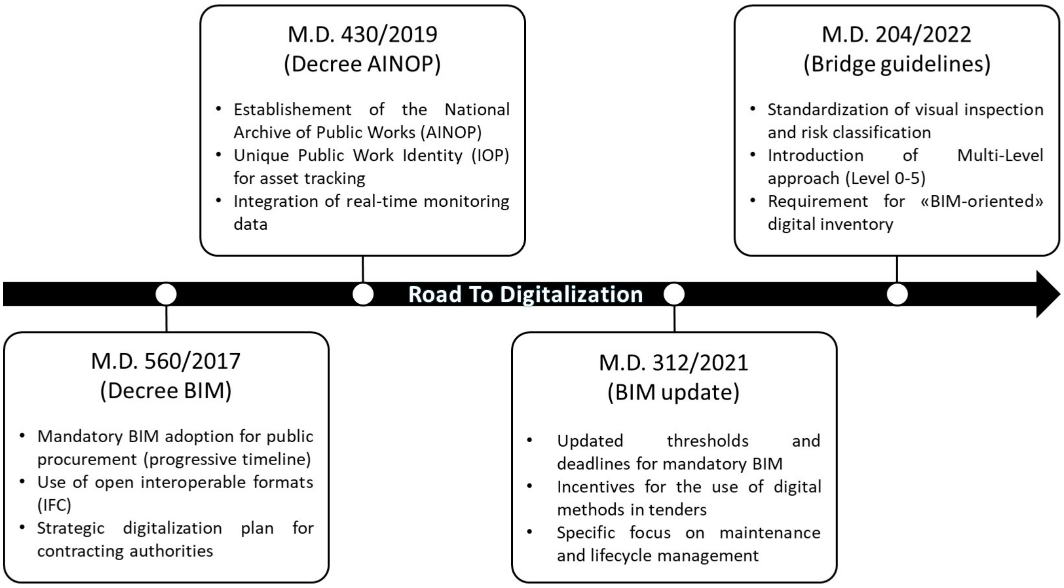


Figure 1.2: Timeline of the italian regulatory framework regarding the digitalization

Furthermore, the operational instructions issued by ANSFISA [ANSFISA, 2022] clarify that the implementation of these guidelines relies heavily on a "Multi-Level Approach", where the complexity of the investigation increases with the criticality of the structure. Specifically, the transition from standard visual inspections to Level 4 (Accurate Safety Assessment) and Level 5 (Resilience and Monitoring) mandates a rigorous quantification of structural parameters. The guidelines specify that instrumental monitoring should not be viewed merely as a data collection exercise, but as a strategic tool to reduce uncertainties regarding material properties and structural behavior. Consequently, the regulation implies that the "Level of Knowledge" (LC - Livello di conoscenza) of an asset cannot rely solely on historical design documents, often missing or incomplete, but must be substantiated by direct experimental evidence. This requirement creates a massive influx of diagnostic data that traditional paper-based archives are ill-equipped to handle, thereby reinforcing the technical necessity for a semantic Digital Twin capable of storing, georeferencing, and processing results from both diagnostic campaigns and continuous monitoring systems.

In this scenario, the digitalization of infrastructure is not an abstract goal but a compliance requirement. The integration of Non-Destructive Testing (NDT) data into semantic BIM environments, the core proposal of this thesis, responds directly to these regulatory demands, providing the technological means to achieve the transparency, objectivity, and efficiency mandated by the Italian law.

1.3 Role of Non-Destructive Technologies in advanced asset management

To bridge the gap between the regulatory demand for objective safety assessment and the limitations of traditional practices, Non-Destructive Technologies (NDT) have emerged as the cornerstone of modern Structural Health Monitoring (SHM). In the context of civil engineering, NDTs are no longer merely diagnostic tools for specific anomalies but have evolved into comprehensive systems for the massive digitization of the built environment. The transition from subjective observation to objective measurement relies on the deployment of advanced geomatics sensors capable of capturing the continuous geometric and radiometric properties of an infrastructure without altering its physical integrity.

The scientific literature considers Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicles (UAVs) to be promising solutions for carrying out the inspection of infrastructure on a larger scale. TLS, as highlighted in a series of scientific papers presented by Lubowiecka et al. in 2009 [9] and Riveiro et al. in 2016 [10], allows for as-is geometry measurements on a millimeter accuracy level, making it possible to identify any deviation, which could not be perceived otherwise. This capability is crucial for establishing a reliable geometric baseline, effectively creating a "zero state" digital reference against which all future degradations can be measured. However, the direct application of raw TLS data for structural displacement measurement presents specific challenges regarding resolution. As noted by Park et al. (2007) [11], standard point clouds typically exhibit coordinate errors in the range of 10 mm, which may be insufficient for precise health monitoring purposes where sub-millimeter accuracy is required. To bridge this gap, advanced post-processing methodologies, such as displacement measurement models based on the least squares approximation of intersecting planes, have been developed to reduce errors to less than 1 mm, achieving deviations of less than 1.6% compared to traditional contact sensors like Linear Variable Displacement Transducers (LVDTs). Unlike traditional monitoring systems such as GPS or accelerometers, which provide data only at discrete sensor locations, this TLS approach enables the reconstruction of the entire deformed shape of a structure. Furthermore, recent studies (Kashani et al., 2015 [12]) have highlighted that the radiometric component of the laser signal (intensity) correlates with physicochemical surface properties, offering a potential proxy for detecting moisture ingress and material degradation before they manifest as visible structural failures.

Nevertheless, linear structures such as bridges and viaducts display complicated accessibility problems that cannot be resolved by sensors on the ground only. In this regard, multi-sensor systems based on unmanned aerial vehicles (UAVs) play a critical role. Nex e Remondino (2014) [13] make clear the flexibility of UAVs in dealing with occlusions when inspecting high-level structure elements such as piers and bearings that do not require using expensive access equipment. By integrating high-resolution photogrammetry with aerial LiDAR, UAVs provide a holistic top-down perspective that complements the bottom-up data from TLS. This multi-scale and multi-sensor approach, often referred to as data fusion, is essential to eliminate blind spots and ensure the completeness of the dataset (Gagliardi et al., 2023 [14]).

In an advanced Asset Management framework, these technologies do not simply replace the human inspector; they augment their cognitive capacity. By providing a navigable, measurable, and repeatable digital replica of the asset, NDTs enable the transition from qualitative condition rating based on visual estimation to quantitative damage assessment based on calculated metrics (areas, volumes, displacement vectors). This objective data stream is the fundamental prerequisite for feeding the predictive models required by modern BMS, ensuring that maintenance decisions are driven by empirical evidence rather than subjective judgement.

1.4 Digitalization and the path towards Digital Twin

The Architecture, Engineering, and Construction (AEC) sector is currently undergoing a profound paradigm shift, transitioning from fragmented, analog documentation to integrated, data-driven ecosystems. Within this context, the Digital Twin has emerged not merely as a technological trend, but as the ultimate objective in infrastructure asset management. However, the trajectory required to achieve a fully functional Digital Twin, defined as a dynamic virtual representation of a physical asset enabling bidirectional data exchange, is nonlinear and fraught with significant challenges. This research is situated within this framework, positing that genuine digitalization transcends the mere conversion of paper documents to digital media; rather, it demands a comprehensive restructuring of geometric and semantic data processing paradigms in asset management. The development of a Digital Twin intrinsically relies on the reliable capture of the physical environment. For existing linear infrastructures, such as bridges and viaducts, a historical obstacle to digitalization has been the severe discrepancy between as-designed documentation and as-is physical conditions. This thesis argues that the geometric veracity of the underlying model forms the indispensable foundation of any reliable Digital Twin. Transitioning from static, low-information models to high-fidelity digital replicas necessitates a digital equivalent that accurately encapsulates the morphological status of the structure. Through the deployment of high-performance, Non-Destructive Testing (NDT) techniques, specifically Terrestrial Laser Scanning and Unmanned Aerial Vehicle (UAV) photogrammetry, a rigorous digital baseline can be established. This intermediate stage creates a unidirectional information flow from the physical to the digital domain, acting as a crucial precursor to the interactive Digital Twin.

Furthermore, the digitalization pipeline addressed in this work tackles the critical challenges of data interoperability and accessibility. A prevalent limitation in conventional engineering practice is the segregation of data into isolated silos: geometric data remains confined within CAD or proprietary point cloud processing software, while semantic information regarding structural health is archived in spreadsheets or analog reports. Recently, substantial research efforts have leveraged Artificial Intelligence (AI) and Deep Learning (DL) architectures, including Graph Convolutional Networks (GCNs), to automate the semantic extraction of structural components directly from raw point clouds (Yang et al., 2023 [15], Jing et al., 2022 [16]). While demonstrating considerable potential, these purely data-driven methodologies are intrinsically constrained by the prerequisite of massive, meticulously annotated training datasets. For unique, complex, or historical civil infrastructures, acquiring such extensive empirical data is often impractical, frequently compelling researchers to rely on synthetic data augmentation strategies. Acknowledging this structural limitation, this thesis pursues an alternative, deterministic methodology. Rather than depending on data-intensive deep learning models, the path towards the Digital Twin advocated herein employs a semi-automated, object-oriented programmatic approach. This framework dismantles traditional data silos by integrating massive reality-capture datasets into structured Building Information Modeling (BIM) environments and, subsequently, into interactive digital platforms via visual programming and customized scripting. This evolution marks a transition from passive data archiving to active data exploitation, wherein the digital model transcends a mere geometric repository to become an interactive instrument for structural diagnosis and decision-making.

Consequently, the path referred to in this section is as methodological as it is technological. It embodies a paradigm shift from a reactive strategy, where digitization is triggered solely by structural failure or specific rehabilitation mandates, to a proactive asset management framework. By establishing a workflow that seamlessly bridges the raw acquisition of point clouds with semantic modeling, thereby circumventing the data bottlenecks associated with DL training, this research fortifies the foundational layers of the Digital Twin. Ultimately, it yields the rigorous geometric and visual baseline required to support the future implementation of predictive AI algorithms, ensuring that the digital counterpart functions not as an idealized abstraction, but as a high-fidelity mirror of the physical infrastructure's reality.

1.5 Research objectives and methodology

The primary objective of this doctoral research is to develop, assess, and optimize an integrated workflow for the inspection and monitoring of linear infrastructures, specifically bridging the gap between advanced geomatic survey techniques and digital asset management platforms. The study is driven by the recognition that while individual technologies for surveying and modeling have reached a high level of maturity, their combined application in standard engineering workflows remains fragmented and often inefficient. Consequently, the research aims to demonstrate how the synergistic use of high-yield Non-Destructive Technologies and interactive virtual environments can significantly enhance the reliability, safety, and speed of inspection procedures compared to traditional visual methods. To achieve this overarching goal, the methodology is structured as a cumulative process of data enrichment and transformation. The initial phase of the research focuses on the optimization of on-site data acquisition. Recognizing the limitations of traditional topographic methods in capturing the complexity of existing structures, the methodology employs a dual approach utilizing both Terrestrial Laser Scanning and UAV-based photogrammetry. The objective here is not simply to collect data, but to determine the optimal acquisition parameters that balance field operational time with the resolution required for structural diagnosis. This involves a rigorous analysis of how different sensor positions, overlap ratios, and environmental conditions influence the quality of the resulting dense point clouds and textured meshes generated in processing software.

Following the acquisition and processing phase, the methodology progresses to the critical task of data integration and semantic modeling. The research investigates the translation of raw surveying data into structured Building Information Models. However, a key specific objective of this work is to overcome the limitations of standard BIM authoring tools when dealing with the high-resolution texture information necessary for visual inspection. To address this, the methodology introduces a novel immersive BIM workflow, incorporating the use of the Unity real-time development platform. This step is designed to test the hypothesis that advanced graphics engine can serve as superior platforms for virtual inspection, allowing for the ingestion of heavy, texturized Wavefront OBJect (OBJ) and Filmbox (FBX) models that retain the visual fidelity of photographs while providing the navigational freedom of a 3D environment. The final component of the methodological framework is the assessment of this digital workflow through the implementation of a virtual inspection loop. This involves the development of custom functionalities within the virtual environment to allow for measurement, annotation, and data extraction. The research aims to prove that a surveyor can effectively identify, classify, and measure defects within the virtual replica with a degree of accuracy comparable to on-site operations, but with drastically reduced risk and logistical costs. This process is cyclical; the methodology includes the procedure for exporting these virtual annotations back into the BIM environment or structural reports, thereby closing the loop between the digital reality captured by the sensors and the semantic reality required by engineers. Through the application of this workflow to selected case studies, the dissertation provides a comprehensive evaluation of the proposed protocols, assessing their technical feasibility and their potential to redefine the standard of care in infrastructure maintenance.

The complete logical flow of this research, moving from the initial Non-Destructive survey to the final asset management integration, is illustrated in Figure 1.3.

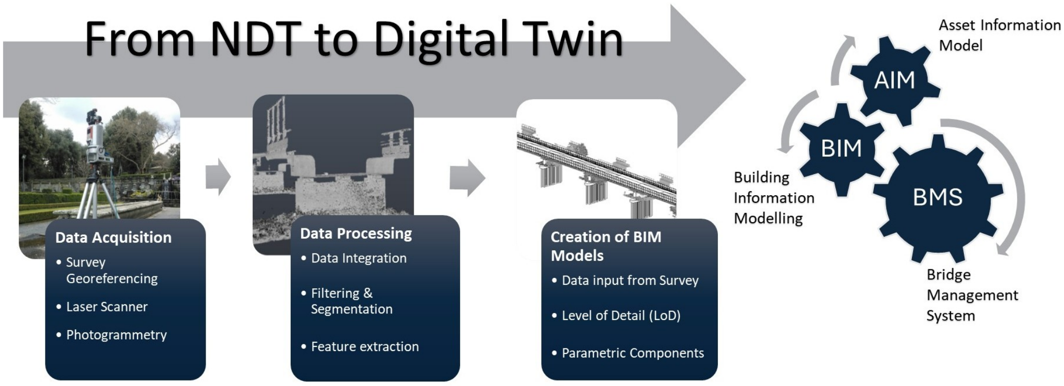


Figure 1.3: General methodological workflow: from NDT data acquisition to Digital Twin integration for Bridge Management Systems

Within this broad framework, the research objectives are not limited to the validation of a single technique for a singular purpose. Although the selection of the case studies presented in this thesis involves distinct infrastructure assets, their selection was not driven by the intention of simply reiterating the same process on comparable systems. Rather, it was aimed at observing the particular contexts in which these highly specialized methods yield the highest value for specific, yet diverse, engineering goals. The underlying rationale is to demonstrate that the path toward digitalization, depicted in the diagram as a progression from Data Acquisition to the Bridge Management System (BMS), is not a rigid, monolithic procedure, but an adaptable process capable of meeting different requirements. Through the application of these methods to achieve diverse results, ranging from geometric reconstruction in complex environments to risk analysis in inaccessible settings, this thesis aims to establish an optimized and multifaceted workflow. The proposed strategy ensures that the method is not limited to a specific use case but rather becomes a versatile tool capable of addressing diverse and unpredictable challenges and difficulties in the lifetime management of civil infrastructure.

Building upon the identified gaps in the current literature, the original contributions of this doctoral thesis are articulated through a holistic, integrated approach. Primarily, this work overcomes the limitations of traditional Scan-to-BIM workflows that rely heavily on the manual, time-consuming interpretation of point clouds. Instead, it introduces a deterministic, semi-automated programmatic methodology. By leveraging visual programming and customized scripting, the proposed strategy significantly accelerates the geometric instantiation of complex linear infrastructures directly from massive Terrestrial Laser Scanning and UAV datasets, drastically reducing the subjectivity and effort inherent in manual modeling. Furthermore, the innovation of this research extends to multi-source data interoperability and active asset management. While contemporary literature frequently isolates geometric surveys from structural health diagnostics, this thesis establishes a rigorous framework where the Building Information Model functions as a dynamic, georeferenced single source of truth. This ensures direct interoperability between high-fidelity reality capture and Bridge Management Systems. Building upon this consolidated database, the research bridges the gap between static 3D representation and immersive monitoring by transposing high-resolution structural models into Virtual Reality (VR) environments. This advancement not only enables remote, high-fidelity visual inspections, effectively decoupling the assessment process from physical site constraints and operational risks, but also sets a robust methodological baseline for change detection across multi-temporal survey campaigns.

Chapter 2

Surveying with Non-Destructive Technologies

In relation to Structural Health Monitoring (SHM) and infrastructure, sophisticated surveying refers to a process of geometric or physical data acquisition with non-contact or minimally invasive techniques, which allow one to accurately describe, through various methods, a topological and condition characterization of a given structure. In this context, a prominent role stands out for Geomatics, which can be considered as a scientific and technological field, whose objective is to combine various aspects such as the science of measurements, sensors, data elaboration, and reference systems, to support engineering analysis.

Crucially, the definition of a rigorous and standardized data acquisition protocol represented, until recently, a significant missing link within the Italian infrastructure management framework. While the introduction of recent regulatory standards, specifically the Guidelines for existing bridges, shifted the paradigm towards a quantitative assessment based on the "Level of Knowledge" (LC), the operational reality remained largely anchored to traditional, analog practices. Consequently, the adoption of the high-performance Non-Destructive Technologies described in this chapter addresses a specific industry urgency: to bridge the gap between the regulatory demand for Digital Twins and the lack of optimized, field-tested acquisition workflows suitable for the massive stock of existing Italian bridges. These techniques, although technologically mature, had not yet been fully integrated or optimized into a cohesive process for the specific constraints of national infrastructure management.

The need for a gradual evolution from traditional, experience-driven visual inspections to a more data-driven method of inspection is, as a matter of fact, a common need, as evidenced in various research literature, for a more appropriate management of infrastructure [17]. As pointed out, for instance, within the visual inspection, although still a valid method of assessment, at least at a first level to abide by current regulations, remains a basically subjective and qualitative process, difficult for comparative purposes over a given period of time [18]. On the other hand, NDTs enable a more objective, quantitative, and geographically referenced assessment, making them more appropriate for monitoring and evaluation purposes [19].

This chapter will offer a critical review of the major non-destructive methods used in the observation of linear civil infrastructures. Contrary to a more fragmented, technique-by-technique analysis, this chapter will offer an integrated outlook, describing in what way a number of diverse sensors and methods complement each other in a multi-scale and multi-modal observation setting.

2.1 Analysis of tradition NDT - Total Station

The Total Station (TS) represents the past and current technical basis of geometric surveys in the field of civil engineering. Contrary to what its name suggests, the total station does not symbolize an obsolete tool but still represents the standard in high-accuracy measurements and geodetic control network formation in deformation measurements and other high-accuracy civil engineering surveys.

Technically, a total station is the integration of angular measurement instruments with the technology of Electronic Distance Measurement, (EDM). The EDM technology uses the phase difference or the time difference of the returned signal, which is transmitted with an electromagnetic wave, preferably in the infrared band, to the reflector or to the reflecting surface. The angular measurements may have subarc second accuracy, whereas the distance measurements have a millimeter level of accuracy (1mm + 1ppm) dependent on the type of the total station.

Typical surveying processes involve the establishment of a reference network with stability, which in most cases is achieved by using permanent reference points tied to non-deforming parts of the structure or topography. This provides a platform with which the data can be measured repeatedly over a certain period, allowing the effect of displacement or rotation to be established. According to Setan and Singh (2001) [20], such networks are fundamental to the coordinate approach, where the analysis of geometric displacements relies on estimated coordinates including their covariance matrices.

In the context of optimizing bridge inspection and maintenance, the application of the TS is not directed towards continuous real-time monitoring using installed sensors, but rather the systematic re-evaluation of geometric parameters over discrete time intervals. This methodology, defined as multi-epoch deformation analysis, involves acquiring coordinates at distinct epochs $(t_1, t_2, \ldots, t_k)$ to identify long-term trends. To ensure rigor, the monitoring network is strictly categorized into:

- Reference points: stations located outside the deformable body, serving as the absolute computational base.

- Object points: targets installed on critical nodes of the bridge to capture structural displacements relative to the stable frame.

It is well recognized that the strengths inherent in total station surveying are millimetric precision, ruggedness, and the ability to trace measurements. However, it is clear that this method has its weaknesses too. These include the inherent discreteness that results in low point densities, the time-consuming nature involved in data collection, and the need for line-of-sight conditions. As noted in research concerning dynamic deformation, the low sampling rate and discrete nature of TS measurements make it difficult to capture high-frequency oscillations or comprehensive surface details compared to other sensors.

Consequently, it is clear that the method is not capable of dealing with complex geometries or surface details such as material degradation, cracking, or spalling. The overall meaning is that the total station is not concerned with providing a comprehensive geometric description for defect detection, but instead offers the necessary infrastructure within which mass data methodologies, like photogrammetry and laser scanning, can be securely rooted. By defining the stable External Reference Frame, the TS provides the Ground Control Points (GCPs) required to register the high-density datasets generated by advanced NDT techniques, ensuring that the visual inspection of material loss and degradation is supported by a rigorous metric skeleton.

2.1.1 Experimental instrumentation

For the experimental field surveys detailed in the subsequent chapters, the research campaign utilized the geodetic equipment provided by the Roads, Railways, and Airports research group of the Department of Civil, Computer Science and Aeronautical Technologies Engineering, of Roma Tre University. Specifically, the establishment of the reference network and the execution of high-precision topographic measurements were conducted using the Leica FlexLine TS07 manual total station.

This instrument is characterized by mid-to-high accuracy standards suitable for civil engineering and structural monitoring applications. Technically, the TS07 is equipped with a high-performance EDM unit capable of operating in both prism and reflectorless modes, which is particularly advantageous for measuring inaccessible points on complex bridge infrastructures. The instrument specifications include:

- Angular accuracy: the goniometric unit offers an angular measurement accuracy of up to 1” (0.3 mgon), supported by quadruple axis compensation to correct for instrument tilt errors.

- Distance measurement accuracy (prism mode): in standard operating conditions using a single prism, the EDM achieves a precision of 1mm + 1.5ppm, ensuring rigorous control of the reference network geometry.
- Reflectorless capability (pinpoint R500/R1000): for direct monitoring of structural elements where prism installation is not feasible, the instrument provides a reflectorless range of up to 500 m with an accuracy of 2mm + 2ppm.
- Environmental robustness: the instrument is rated IP66 for dust and water protection, ensuring operational reliability during extended field campaigns under varying environmental conditions.

Table 2.1: Technical specifications of the Leica FlexLine TS07 Total Station

Parameter	**Specification**	**Note**
Instrument Type	Manual Total Station	Leica FlexLine Series
Angular Accuracy	1" (0.3 mgon)	ISO 17123-3
EDM Accuracy (Prism)	1 mm + 1.5 ppm	ISO 17123-4
EDM Accuracy (Non-Prism)	2 mm + 2 ppm	PinPoint R500 / R1000
Range (Non-Prism)	Up to 500 m	Kodak Gray Card (90% refl.)
Compensator	Quadruple axis	Setting accuracy 0.5"
Environmental Rating	IP66	Dust & Water protection

The adoption of this specific instrumentation allowed for the definition of a stable and accurate external reference frame, which serves as the metric constraint for the subsequent integration of mass-data acquisition techniques described in this thesis. The key technical specifications are detailed in Table 2.1, while the experimental setup during the field campaign is shown in Figure 2.1.

2.2 Photogrammetry

The domain of geomatics and non-contact inspection has been revolutionized by the paradigm shift from traditional photogrammetry to Computer Vision-based approaches, specifically Structure from Motion (SfM) and Multi-View Stereo (MVS). Unlike classical stereophotogrammetry, which relied on rigorous strip arrangements and calibrated metric cameras, SfM algorithms enable the reconstruction of sparse 3D geometry from unstructured image sets acquired with consumer-grade sensors [21]. The mathematical foundation relies on the automatic extraction of invariant features, distinctive geometric or radiometric points, using algorithms such as SIFT (Scale Invariant Feature Transform) [22]. These features allow for the robust matching of homologous points across multiple overlapping images, facilitating the simultaneous

Figure 2.1: Total station in site

estimation of internal camera parameters (self-calibration) and external orientation (pose estimation) through Bundle Adjustment procedures [23].

Following the sparse reconstruction, MVS algorithms densify the point cloud by computing depth maps for each pixel, generating high-density geometric data comparable, in terms of point count, to Terrestrial Laser Scanning (TLS). However, a fundamental geometric constraint defines purely image-based modeling: SfM operates on the principle of projective geometry. In the absence of external metric constraints, the reconstructed model is defined only up to a similarity transformation. This implies that while the angular relationships and shape proportions are preserved, the translational vector and the scaling factor remain arbitrary [11]. Consequently, the model exists in a dimensionless space. To transition from this relative image space to an absolute object space (e.g., a cartographic projection or a local metric system), the integration of Ground Control Points (GCPs) or reliable scale bars measured with geodetic accuracy is strictly mandatory.

Despite these geometric caveats, photogrammetry offers unique capabilities for Structural Health Monitoring (SHM). Its most significant contribution is the generation of high-fidelity orthomosaics and textured meshes. While active sensors like LiDAR record intensity values, photogrammetry captures the full radiometric spectrum

(RGB), which is indispensable for the semantic interpretation of defects such as efflorescence, rust staining, or dampness patterns. Nevertheless, the achievable accuracy is governed by the Ground Sampling Distance (GSD), which acts as the limiting factor for spatial resolution. Obtaining sub-millimeter accuracy requires proximity to the object and focal lengths that may limit the field of view, necessitating a trade-off between coverage speed and inspection resolution.

2.2.1 Preliminary application: the case study of Priverno bridge

To empirically delineate the operational boundaries of photogrammetry in rapid inspection scenarios, specifically addressing the issue of scale ambiguity, an experimental campaign was conducted on a reinforced concrete overpass in Priverno, Latina. The structure provided an optimal testbed due to the accessibility of the pier-deck interface from the ground level, permitting a terrestrial acquisition workflow without the logistical complexity of aerial platforms (Figure 2.2).

Figure 2.2: Priverno Bridge: Structural context and accessibility.

The survey methodology involved the acquisition of a convergent dataset focusing on the substructure elements (piers and beams). The processing pipeline was executed in Agisoft Metashape, utilizing a standard SfM-MVS workflow: feature matching, camera alignment, and dense cloud generation. Crucially, to simulate a worst-case scenario typical of rapid post-disaster assessments or preliminary scouting, the project was processed relying exclusively on the intrinsic EXchangeable Image File Format (EXIF) data of the images, intentionally omitting measured GCPs or scale bars. This approach aimed to verify the magnitude of the drift inherent to unconstrained monocular SfM (Figure 2.3).

Quantitative analysis of the generated model highlighted the critical limitations regarding scale ambiguity. A dimensional check was performed on the pier cap width. The digital measurement extracted from the unscaled model returned a length

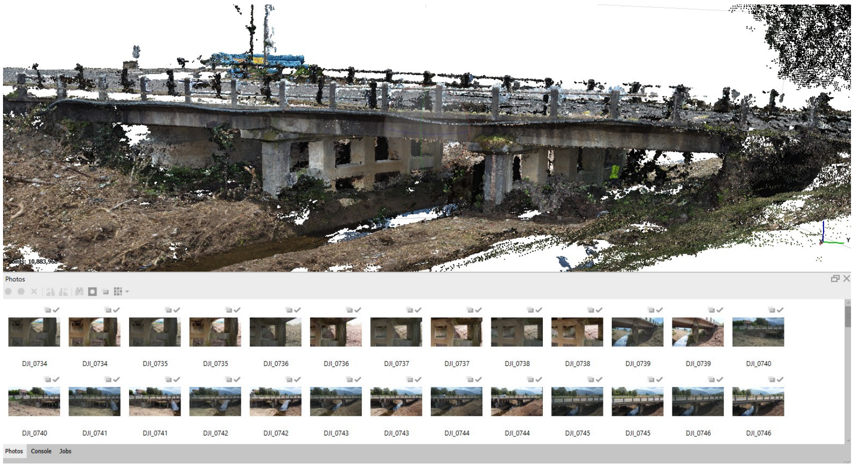


Figure 2.3: 3D Photogrammetric reconstruction (Sparse Cloud visualization).

of 1.54 meters. Conversely, validation against the as-built technical drawings and direct in-situ tape measurements confirmed the actual dimension to be 1.42 meters (Figure 2.4).

Figure 2.4: Dimensional discrepancy analysis: Digital measure (1.54 m) vs. Real dimension (1.42 m).

This discrepancy corresponds to a relative error of approximately 8.5%, a value that remains unacceptable for structural engineering verification. The experiment elucidates that while SfM algorithms can reconstruct the visual morphology with high qualitative fidelity, they fail to provide reliable metric data in the absence of external referencing. In operational contexts where physical access to the structure is precluded (e.g., high-altitude viaducts or spans over water), preventing manual measurement of reference lengths, reliance on unconstrained photogrammetry poses a significant risk. This finding reinforces the necessity of establishing a topographic network (via Total Station) prior to the photogrammetric survey to rigidly constrain the bundle adjustment solution.

2.2.2 Limitations and synergies

Beyond the metric scaling issues, the application of photogrammetry to civil infrastructure encounters distinct radiometric and environmental limitations. A primary challenge in concrete inspection is the textureless surface problem. SfM algorithms rely on the identification of high-contrast features; however, new concrete surfaces or painted steel often exhibit homogeneous radiometric properties. As demonstrated by Hirschmuller (2008) [24], low-texture regions can lead to failures in the stereo-matching process, resulting in noisy point clouds or reconstruction holes.

In addition, photogrammetry is an example of a passive sensing technology that relies entirely on naturally occurring sources of light for operation. The presence of unevenly distributed light and dark areas within the scene, including extreme brightness or severe shadowing (such as those found under bridges), can diminish the quality of the resulting digital photographs and hinder the ability to detect surface conditions. Because of these limitations, the use of photogrammetry for inspecting tunnels and dark environments is not an optimal method of inspection without the addition of artificial light sources (which adds additional weight and requires additional logistical support).

Notwithstanding these limitations, photogrammetry remains a critical component of the SHM toolkit. Its strength lies not in standalone geometric accuracy, where LiDAR or Total Stations often prevail, but in semantic richness. By integrating photogrammetric textures with the geometric rigidity of LiDAR (sensor fusion), it is possible to achieve a holistic Digital Twin: the active sensor ensures metric correctness and penetrates vegetation, while the passive sensor provides the high-resolution color data necessary for AI-based crack detection and corrosion mapping [25].

2.3 Laser Scanning

TLS is an established non-destructive technique to represent very accurately all geometric features of civil infrastructure. Its fundamental principle relies on Light Detection and Ranging (LiDAR) technology. Laser pulses are transmitted toward the object being surveyed, and as they strike and are reflected off the surface of the object, the distance travelled is determined. Ranging technologies in TLS can be divided into two categories: Time of Flight (ToF) and Phase Shift. ToF technologies, which are optimal for long range measurements, determine distance based upon the time required for each laser pulse to travel to the object and return to the source or laser scanner. In contrast, Phase Shift technologies determine distance based upon the phase difference between the modulated continuous wave emitted from the laser scanner, which provides faster measurements, at a shorter range.

A crucial benefit of TLS is its capability to deliver extremely dense and precise point cloud data, often capturing millions of points in a single scan with millimeter-level resolution. Moreover, as an active remote sensing method that generates its own energy source, TLS holds clear operational advantages over photogrammetry in environments with poor or variable lighting conditions. Beyond geometric coordinates (X, Y, Z), modern laser scanners record the intensity (or reflectance) of the return signal for each point. This radiometric component, influenced by the angle of incidence and distance, has been proven in studies within Remote Sensing and Automation in Construction literature to correlate with specific material characteristics. Recent research indicates that laser intensity can be effectively exploited to detect moisture content anomalies and surface deterioration in concrete structures, adding a diagnostic layer to the geometric survey.

The general TLS workflow is typically conducted in a stop-and-go manner, requiring the scanner to be positioned on a tripod at multiple stations to minimize occlusions and shadow zones. These individual scans are subsequently combined into a single coordinate system through registration processes, which generally rely on target-based artificial markers or cloud-to-cloud algorithms, such as the Iterative Closest Point (ICP).

2.3.1 Evaluation of automatic registration: preliminary case studies

To critically evaluate the reliability of modern automatic registration workflows, often marketed as target-less solutions, preliminary experimental campaigns were conducted during the initial phase of this research. The objective was to assess whether high-end hardware and proprietary software could replace the traditional topographic approach in complex infrastructure scenarios.

The Priverno Bridge experiment. The first test field was the reinforced concrete bridge in Priverno, previously surveyed via photogrammetry. For this acquisition, a Trimble X9 terrestrial laser scanner was employed, characterized by high-speed acquisition and millimetric precision, are summarized in Table 2.2. This instrument features an automatic in-field registration system designed to align scans without external targets, leveraging an Inertial Measurement Unit (IMU) and cloud-to-cloud matching algorithms. A total of eight scans were performed: six positioned to capture the substructure (piers and intrados) and two for the road surface. The raw data was processed directly using the proprietary software, generating a unified point cloud exported in .LAS format (Figure 2.5).

During the modeling phase, a detailed inspection of the point cloud revealed ge-

Table 2.2: Technical specifications of the Trimble X9 terrestrial laser scanner

Parameter	Description
Instrument Model	Trimble X9
Measurement Principle	High-speed digital Time-of-Flight (ToF)
Scan Rate	Up to 1.000.000 pts/sec (1 MHz)
Range	0.6 m – 150 m
Field of View (FoV)	360° (horizontal) × 282° (vertical)
Range Accuracy	< 2.0 mm
Range Noise	< 1.5 mm @ 30 m
Angular Accuracy	< 16” (vertical/horizontal)
3D Point Accuracy	2.3 mm @ 10 m / 3.0 mm @ 20 m
Tilt Compensation	Automatic dual-axis compensator (±10° range, < 3” accuracy)
Registration System	Automatic in-field (IMU-based and Cloud-to-Cloud)
Laser Class	Class 1 (Eye Safe, IEC EN60825-1)

Figure 2.5: a) Setup of laser scanner, b) Acquired point cloud

ometric inconsistencies that contradicted the software's quality report. While the registration report indicated an average residual error of approximately 5 millimeters, a cross-section analysis of the structural beams exposed a significant misalignment. A distinct double surface effect was visible, indicating a registration drift of approximately 2 centimeters between adjacent scans (Figure 2.6). Considering the high nominal accuracy of the instrument, detailed in Table 2.2, this misalignment significantly exceeds the expected measurement noise. Although this error was relatively minor in the context of a small bridge, it highlighted a critical issue: purely cloud-to-cloud registration can suffer from slippage in linear environments with repetitive geometries (like parallel beams), leading to models that are statistically correct according to the software but geometrically flawed.

Figure 2.6: "Double-surface" error

The Circus of Maxentius: error propagation in linear scanning. To investigate the impact of this phenomenon on a larger scale, a second extensive survey was conducted at the Circus of Maxentius, an archaeological complex on the Appian Way in Rome (Figure 2.7). The site geometry, characterized by a long elliptical track, necessitated a linear scanning path. The survey plan involved a closed-loop trajectory, starting from a specific point, circumscribing the entire track, and returning to the start position to close the loop. Over 80 scans were performed using the same automatic registration workflow (Figure 2.8).

The processing of this massive dataset proved computationally demanding, consuming over 250 GB of RAM merely to load and visualize the data, highlighting the big data challenges inherent in large-scale TLS projects. More critically, the accumulation of registration errors resulted in a catastrophic failure of the loop

Figure 2.7: Circus of Maxentius

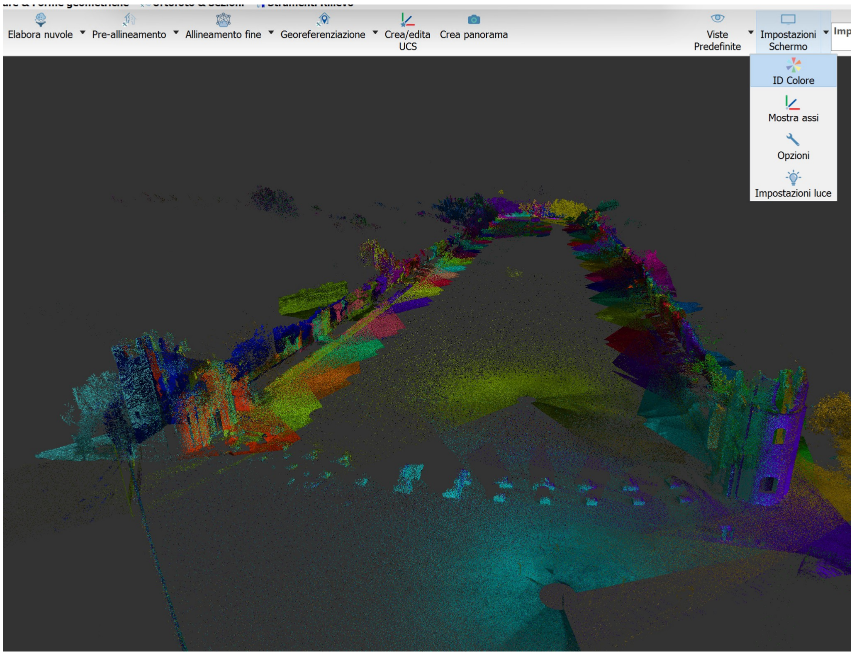


Figure 2.8: Cloud of points of Circus of Maxentius with Color ID

closure. Since the software aligned scans sequentially (Scan 1 to 2, 2 to 3, etc.), the small residual errors in each link propagated along the trajectory. When the final scan was registered to the initial one, a spatial discrepancy of 1.47 meters was observed (Figure 2.9). This deviation demonstrates the inherent limitation of employing TLS as a standalone tool for linear infrastructures without external constraints.

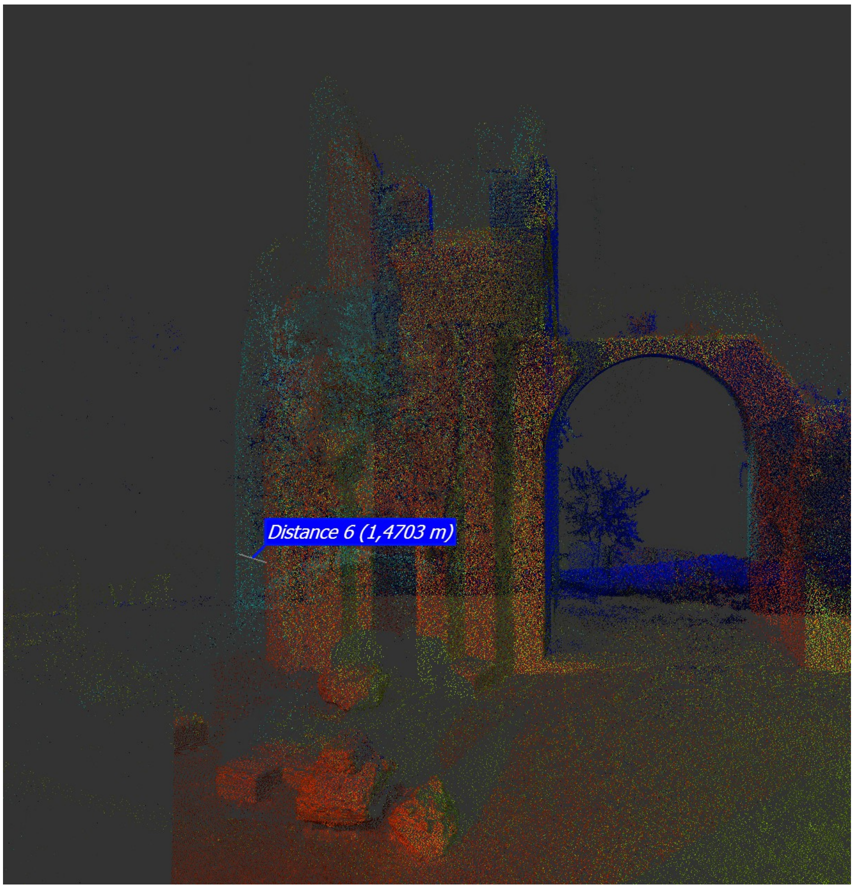


Figure 2.9: Difference of two survey

While the instrument offers millimeter precision for a single measurement, the lack of a rigid topographic network (measured via Total Station) leads to drift and deformation in the global model. Consequently, these preliminary findings confirmed that for the rigorous monitoring of linear assets, TLS must be integrated with a primary geodetic network to constrain error propagation, a methodology that was subsequently adopted for all following case studies in this thesis.

2.4 UAV-based multisensor systems

Unmanned Aerial Systems (UAS) or drones represent a great paradigm change in the area of Civil Infrastructure Inspection. Conventional practices rely almost exclusively on direct physical accessibility via potentially expensive under-bridge inspection units; they often require scaffolding or rope-access techniques. On the other hand, UAS systems offer a paradigm of remote sensing that significantly improves the ability to collect data. In the view of Nex and Remondino (2014) [13], UAS systems offer a versatile and efficient means that can fill the gap that exists between ground surveying practice and the area of large-scale mapping. This suits the need for a multi-scale view that characterizes Structural Health Monitoring (SHM). Using UAV technology in the inspection of bridges embodies not only the current trend but the rising need for efficient, safe, and reliable monitoring. In the study by Chan et al. (2015) [26], the deployment of UAVs resulted in a significantly reduced cost of inspection compared to the traditional method, with a corresponding improvement in the safety of the inspection personnel as a result of eliminating the need to work at height. In addition, the capability of the UAV to carry a range of sensors allows the structure to undergo a multi-modal inspection, not merely relying on geometric parameters but also involving thermal and visual parameters, which are indispensable for the identification of a wide range of defects.

The use of unmanned airborne vehicles (UAVs) for infrastructure inspection has a number of unique benefits over more traditional approaches, especially with regard to accessibility and data quality. First and foremost, the unique ability of these devices to inspect regions difficult or impossible to access with more traditional equipment, such as the undersides of complex bridge decks, the top parts of high piers, and structural features over water or over busy roads, is notably greater [27]. On top of this improved accessibility comes the fact that their use to replace human inspectors in dangerous environments reduces the risk of accidents to near zero as they implement the principle of "Safety by design". From a more logistical and operational point of view comes a faster inspection and action cycle compared to more traditional inspection approaches which often necessitate the temporary closure of a traffic route to accommodate inspection activities. As a direct and immediate result of the faster inspection and action cycles mentioned above comes a substantial reduction of direct inspection costs as well as the more complex and difficult to calculate economical impacts of traffic congestion [28]. In addition to these factors comes the fact that modern models of these devices possess a higher level of imaging resolution when compared to previous models and are often equipped with sensors which make them particularly adept at capturing high levels of detailed structural data to the point where they are able to identify minute structural defects, such as a hairline fracture, that might easily go unseen during a standard human inspection. As a direct function of the operational abilities of these devices comes the ability to produce a fully digitized and georeferenced structural map which offers a level of objective interpretability of structural defects as they progress over time.

UAV deployment is also associated with a number of limitations, which need to be managed properly in order to maintain the continuity of efficient deployment. Limitations in terms of regulatory measures form a major setback because UAV operation involves a number of stringent guidelines of the EASA/ENAC regulations, especially when flying over critical infrastructure or in residential areas. Acquiring the required authorization for certain operations, like the Beyond Visual Line of Sight (BVLOS) flight, can also prove quite cumbersome. Additionally, the nature of UAV operations involves a number of concerns in terms of the prevailing environmental conditions. For instance, the presence of high wind speeds, rainfall, fog, or a lack of proper lighting conditions can form a major setback in the level of UAV performance and the quality of the produced data. High data amounts acquired in multi-sensor surveys make processing a major concern because of the required processing power to avoid bottlenecks. There are technology limitations in terms of the sensors because, despite the high technology involved, the UAV LiDAR technology often lacks the required level of accuracy and point density compared to the TLS. Finally, the limited flying duration of the UAVs often requires proper mission planning as well as constant replacement of the batteries in the case of comprehensive inspections.

2.4.1 Regulatory framework and operational categories

The Italian regulatory framework for using UAVs over critical infrastructure is aligned with the harmonised European Union Aviation Safety Agency (EASA) regulations 2019/947 [29] and 2019/945 [30] at the national level, with implementation assigned to the ENAC (Ente Nazionale per l'Aviazione Civile). This framework eliminates the traditional division between recreational and commercial operations and is focused on classifying operations based on their risk level.

There are three categories of UAV operations: Open, Specific and Certified. For infrastructure inspection purposes there are two relevant sub-scenarios:

- Light UAS (< 250g): light Unmanned Aircraft Systems (UAS) have a maximum takeoff mass (MTOM) that is below 250 grams (i.e., the Class C0 category). Because of this small size, they do not operate under the same restrictions as heavier platforms. Light UAS can hover over people who are not participating in the operation (but cannot fly over large groups of people). Furthermore, they do not require remote pilot competency certificates (i.e., they do not fall under the Open A1 subcategory). The characteristics of being very agile and having low levels of kinetic energy make light UAS perfectly suited for inspecting enclosed locations or flying in urban areas with little or no administrative overhead.

- Enterprise systems: which are larger platforms that support more complicated, advanced payloads, will generally fit within the Specific category when flying Beyond Visual Line of Sight (BVLOS) or very close to significant/critical infrastructure. The operation of these platforms will require a complete Safety Operations Risk Assessment (SORA) process, which must include the approval of both the Ente Nazionale per l'Aviazione Civile (ENAC) and the Ente Nazionale per l'Aviazione (ENAV), particularly for operations within controlled airspace or over sensitive areas (e.g., archaeological parks or airports).

The research activities conducted within the Department of Civil, Computer Science and Aeronautical Technologies Engineering employed a dual-platform strategy to maximize operational efficiency.
Close-range visual inspections are now made possible with the advent of Light UAS such as the DJI Mini 3 Pro. Modern Micro-UAVs, despite their small stature, feature high-quality large sensors (1/1.3-inch CMOS) which are capable of capturing high-resolution imagery to detect cracks. The main benefit is their manoeuvrability; they are able to navigate through complex geometries (e.g., between bridge girders or inside box girders) that would be unsafe for larger drones to fly through.
In order to obtain as much detailed information as possible during the inspection process, comprehensive Enterprise level heavy-lift system solutions such as those described above, (such as the DJI Matrice 350 RTK), are an essential tool. Given the high level of wind resistance, Real Time Kinematic-RTK positioning accuracy, and multi-payload capability of these systems, these tools provide the perfect means to perform high viaduct inspections.

- Full-Frame photogrammetry (Zenmuse P1): integrating a full-frame sensor (45 MP) allows for the acquisition of sub-millimeter Ground Sampling Distance (GSD) even from safe flight distances. This high radiometric quality is essential for the photogrammetric reconstruction of fine texture details.

- Airborne LiDAR (Zenmuse L1/L2): while UAV-based LiDAR generally exhibits higher noise levels compared to TLS, it offers the unique advantage of an aerial viewpoint and vegetation penetration (multi-echo). This allows for the reconstruction of the bridge deck and upper structural elements that remain occluded in ground-based TLS surveys.

- Thermal Imaging: payloads such as the Zenmuse H20T enable thermographic inspection. By detecting thermal anomalies, these sensors can identify sub-surface defects like delamination or moisture retention under the pavement, which are invisible to standard RGB sensors.

The technical specifications of the equipment utilized in this research are detailed in Table 2.3.

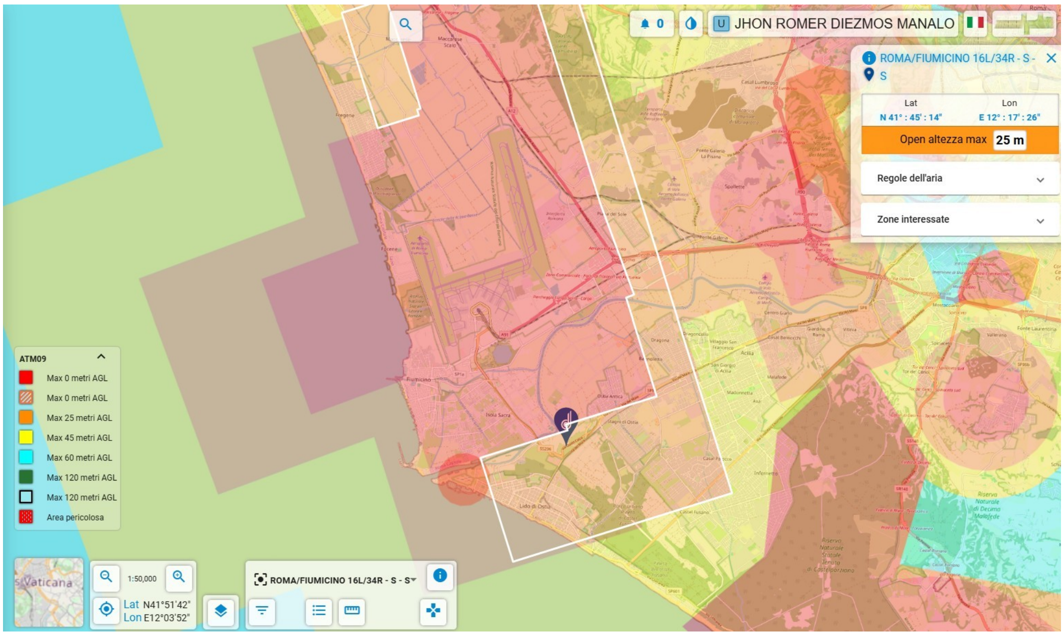
Table 2.3: Technical specifications of the UAV platforms and payloads

System / Sensor	Key Technical Specifications	Primary Application
DJI Mini 3 Pro *(Light UAV)*	• Sensor: 1/1.3" CMOS (48 MP) • Lens: 24mm eq. f/1.7 • Weight: < 249 g • Flight Time: ~34 min	Visual inspection in confined spaces; Urban overflight.
DJI Matrice 350 RTK *(Enterprise Platform)*	• Max Payload: 2.7 kg • Ingress Protection: IP55 • Flight Time: ~55 min • Positioning: RTK (±1 cm+1ppm)	Heavy-lift carrier for multi-sensor surveying (LiDAR / Photogrammetry).
Zenmuse P1 *(RGB Payload)*	• Sensor: Full-frame (45 MP) • Shutter: Global Mechanical • Lens: 35mm (interchangeable) • Min. Interval: 0.7 s	High-accuracy photogrammetry; Nadir and Oblique mapping.
Zenmuse L1 *(LiDAR Payload)*	• Method: Livox Lidar + RGB • Point Rate: 240,000 pts/s • Returns: up to 3 echoes • Accuracy: 5 cm (vertical) @ 50 m	Vegetation penetration; DTM generation; Powerline inspection.

2.4.2 Preliminary case study: Ostia Antica archaeological park

In order to test the functionality of the Enterprise system in a highly complex and regulated environment, a pilot survey was performed at Ostia Antica Archaeological Park. The research was focused on the Domus della Fortuna Annonaria (House of Fortuna Annonaria - V, II, 8), a prestigious residential complex dating back to the 2nd century AD (Antonine period) and modified in the 4th century. The site derives its name from a statue found in the courtyard representing the goddess Fortuna, associated with the imperial grain supply annona.

The site poses unique logistical challenges due to its proximity to the Leonardo da Vinci International Airport (Fiumicino). Specifically, the archaeological park lies within the approach path of runways 16L/34R. According to the D-Flight cartography (EASA Open Category), the area is classified under strict vertical limits, capping flight altitude at a maximum of 25 meters AGL (Above Ground Level) (Figure 2.10).



Lat N 41° : 45' : 14"
Lon E 12° : 17' : 26"
Open altezza max 25 m

Lat N41°51'42"
Lon E12°03'52"

Figure 2.10: D-flight Site

Prior to operations, official authorization was requested and granted by the Archaeological Park Authority. The flight mission was subsequently coordinated via the D-Flight portal to ensure full compliance with the strict safety zones enforced by the Italian Civil Aviation Authority (ENAC).

Drawing from the lessons learned in the previous bridge experiment, where the lack of metric constraints led to scale ambiguity, this survey adopted a rigorous topographic approach. A ground control network was established using eight artificial targets (GCPs) distributed strategically across the site: at least one marker was placed in every accessible room of the Domus, with redundant points in critical areas.

The coordinates of these Ground Control Points were acquired using a hybrid topographic method to ensure centimeter-level accuracy:

- Global Positioning: a Leica Zeno GG04 Plus smart antenna was employed to fix the primary reference points via RTK (Real-Time Kinematic) corrections.
- Local Precision: to overcome potential GNSS signal multipath caused by ancient walls, a Total Station was used to traverse from the GNSS-fixed points to the specific targets within the rooms.

The technical specifications of the GNSS receiver utilized for establishing the reference frame are detailed in Table 2.4.

Table 2.4: Technical specifications of the Leica Zeno GG04 Plus GNSS Smart Antenna

Parameter	Specification
Channels	555 channels (multi-frequency)
Satellite Signals	GPS, Glonass, BeiDou, Galileo, QZSS, SBAS
RTK Accuracy	Horizontal: < 1 cm + 1 ppm Vertical: < 2 cm + 1 ppm
Update Rate	Up to 20 Hz
Connectivity	Bluetooth v4.2 LE (for tablet integration)
Ingress Protection	IP68 (Dust tight and waterproof)

The photogrammetric acquisition was executed using the DJI Matrice 350 RTK equipped with the Zenmuse P1 full-frame sensor. To comply with the regulatory ceiling of 25 meters, the flight altitude was set to 20 meters AGL. This low-altitude configuration, combined with the 35mm lens of the P1, resulted in an exceptionally high Ground Sampling Distance (GSD). Theoretical calculation of the GSD for this specific setup yields:

$$GSD = \frac{H \cdot p}{f} \approx \frac{20\,m \cdot 4.4\,\mu m}{35\,mm} \approx 2.5\,mm/pixel \tag{2.1}$$

where H is the flight height, p is the pixel pitch, and f is the focal length. This sub-centimeter resolution (approx. 2.5 mm) ensured that even minute details of the masonry textures were captured. A total of over 500 images were acquired. The Matrice 350 RTK leveraged its internal RTK module to tag each image with precise coordinates at the moment of exposure. Figure 2.11 and Figure 2.12 illustrates the operational setup, showing the UAV ready for takeoff with visible ground targets and the topographic survey operations.

The dataset was processed in Agisoft Metashape. Unlike the previous test, the bundle adjustment was rigidly constrained by the measured GCPs, resulting in a metrically reliable model. Two significant outputs were produced during the project:

Figure 2.11: Field operations at the Domus of the Annona: DJI Matrice 350 RTK pre-flight check with visible GCP

Figure 2.12: Total Station survey for target coordination

the first output was a 3D high-density point cloud, and the second output was a textured 3D mesh in OBJ format 2.14. The high resolution texture maps were created from the sub-centimeter imagery, and they produced a photorealistic Digital Twin that can be utilized effectively for immersion within virtual reality (VR) environments, as detailed in subsequent chapters of this thesis document. Figure 2.13 shows the reconstructed geometry of the object and the camera network distribution, and it highlights the significant amount of overlap between cameras during the flight of the UAV.

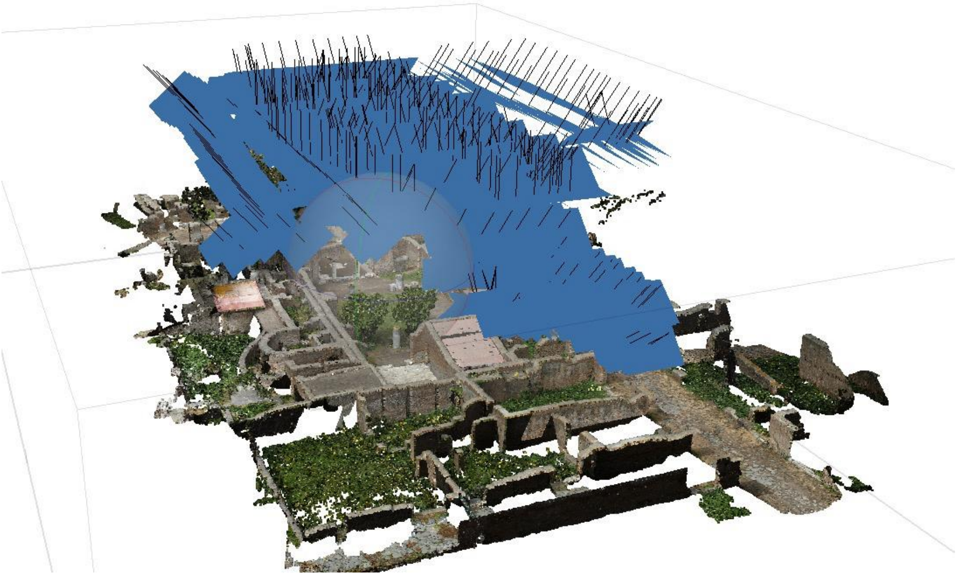


Figure 2.13: Visualization of the acquired photogrammetric block. The blue frustums represent the spatial position and orientation of the images

Figure 2.14: High-fidelity 3D textured mesh of the Domus della Fortuna Annonaria.

2.4.3 Critical analysis and methodological limitations

While the UAV photogrammetry provided excellent coverage of the wall crests, planimetry, and open courtyards, the experiment highlighted specific limitations inherent to a single-sensor approach. The Domus of the Annonaria features several rooms that retain partial roofing or barrel vaults. Since the Matrice 350 RTK is a large enterprise platform (approx. 90 cm diagonal wheelbase), flight within these confined, covered spaces was not feasible due to safety risks and signal degradation. Consequently, the resulting 3D model, although extremely detailed externally, suffered from data occlusion in the interior spaces (shadow zones).

This limitation demonstrated that while aerial photogrammetry is powerful for the external planimetry, it is insufficient for a holistic documentation of complex heritage structures with mixed indoor-outdoor environments. This finding catalyzed the definition of the integrated workflow presented in the following section, which proposes the fusion of UAV data with Terrestrial Laser Scanning (TLS) and terrestrial photogrammetry to resolve occlusions and achieve comprehensive 3D documentation.

2.5 Georeferencing and data integration

The previous sections have analyzed Non-Destructive Technologies (NDT) as individual tools, highlighting the specific capabilities and intrinsic limitations of Terrestrial Laser Scanning (TLS), Photogrammetry, and UAV-based systems. However, in the context of complex infrastructure monitoring, the reliance on a single acquisition methodology rarely suffices to provide a comprehensive and occlusion-free representation of the asset. Linear infrastructures such as bridges are characterized by significant spatial extension and complex geometries that often generate blind spots for ground-based sensors, while aerial sensors may lack the resolution for detailed under-deck inspection. Consequently, the transition from fragmented survey data to a holistic Digital Twin requires a rigorous Data Integration strategy. This process is not merely the superposition of different visual outputs but constitutes a geometric and semantic fusion where multiple datasets are merged into a single, coherent, and measurable environment.

The fundamental prerequisite for effective multi-source integration is rigorous georeferencing. This process involves transforming the local coordinate systems of individual sensors, such as the internal reference frame of a laser scanner or the arbitrary scale of a Structure-from-Motion model, into a unified, global cartographic reference system (e.g., ETRS89/UTM or a local geodetic datum). Without this common spatial framework, data from different epochs or sensors cannot be reliably compared, rendering 4D monitoring (time-lapse analysis) impossible.

The methodology adopted in this research relies on the establishment of a Primary Topographic Network to serve as the geometric skeleton for the entire survey. Before the deployment of mass-data acquisition sensors (TLS or UAVs), a set of high-visibility artificial targets, such as spherical targets for TLS and checkerboard Ground Control Points (GCPs) for photogrammetry, are materialized within the inspection site. The positions of these targets are measured with high-precision instruments, specifically a Total Station and GNSS (Global Navigation Satellite System) receivers. The accuracy of this primary network dictates the overall metric quality of the integrated model; measuring targets with a Total Station provides a constraint that limits the error propagation inherent in cloud-to-cloud registration algorithms or aerial triangulation.

Once the common reference frame is established, the integration process follows a hierarchical co-registration workflow. This strategy exploits the complementary nature of the sensors to eliminate data gaps:

- Terrestrial Laser Scanning (TLS) integration: TLS acts as the reference for high-fidelity geometry. The individual scans, acquired from ground positions to capture piers, abutments, and the deck intrados, are registered together using the topographic targets. This creates a rigid base model with millimeter-level accuracy but potential voids on the upper surfaces due to the scanner's line-of-sight limitations.
- UAV data fusion: the data acquired via UAV (LiDAR or Photogrammetry) is then integrated to complete the model. The UAV datasets are processed using the same set of ground control points (GCPs) surveyed with the Total Station. This ensures that the aerial point cloud, covering the bridge deck, road surface, and inaccessible upper elements, aligns perfectly with the terrestrial data.
- The integrated point cloud: the result of this fusion is a comprehensive, multi-source point cloud that seamlessly combines data derived from distinct instrumentation. Far from being a mere superposition of coordinates, this unified environment represents a multi-modal dataset characterized by a superior information density. It effectively merges the high metric precision and intensity data typical of TLS with the photorealistic texture and complete coverage provided by UAV systems. This mutual enrichment ensures that geometric anomalies are corroborated by high-resolution radiometric attributes, significantly enhancing the interpretability of the asset and providing a robust, information-rich basis for the subsequent semantic modeling.

This integrated approach enables the cross-referencing of data. For instance, the radiometric consistency of the laser intensity can be cross-referenced with the high-resolution RGB texture from photogrammetry to distinguish between geometric anomalies (e.g., material loss) and superficial staining. As demonstrated by Yang et al. (2015) [31], the fusion of TLS and UAV data significantly improves the completeness and reliability of 3D reconstruction for structural monitoring, providing a robust baseline for the subsequent phases of segmentation and semantic modelling (Scan-to-BIM).

Ultimately, this consolidated workflow directly addresses the operational gap highlighted at the beginning of this chapter, moving beyond fragmented practices towards a standardized acquisition protocol. The overarching methodology is schematically summarized in Figure 2.15. The diagram highlights the hierarchical dependency of the survey: the Topographic Network serves as the foundation, constraining the mass-data generated by Terrestrial Laser Scanning and UAV Systems. This multi-source approach ensures that the final Integrated Point Cloud overcomes the limitations of individual sensors, such as drift, occlusion, or scale ambiguity, delivering the high-fidelity geometric and radiometric base required to satisfy the "Level of Knowledge" demands for Digital Twin generation.

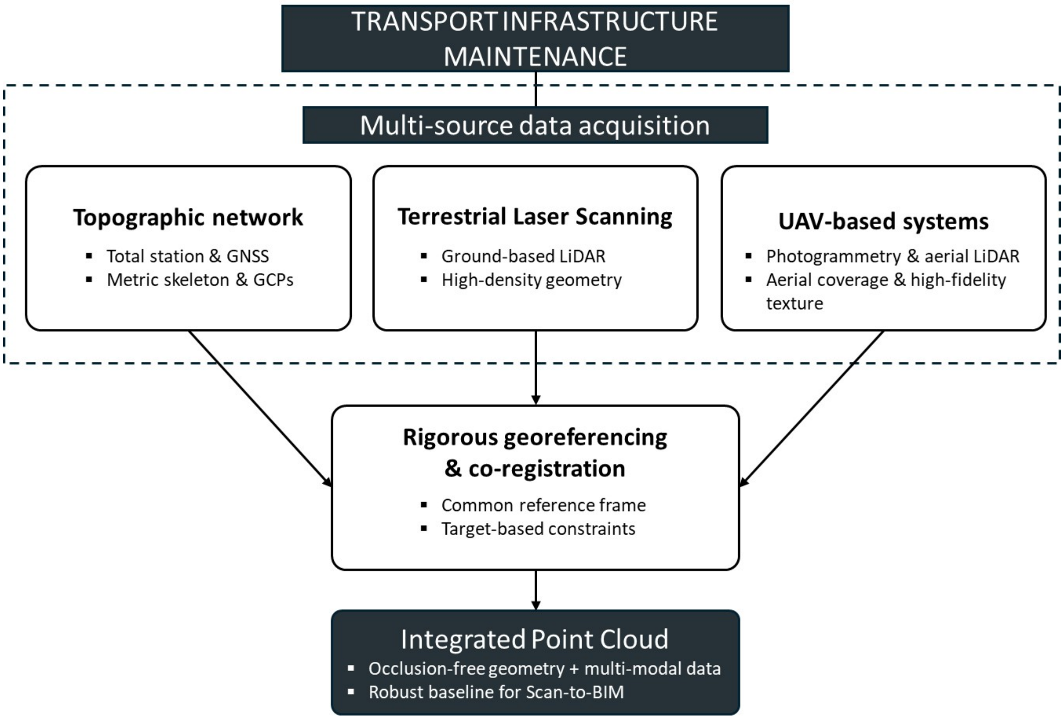


Figure 2.15: Conceptual framework of the multi-source surveying methodology

Chapter 3

Point Cloud Processing and Data Fusion

The point cloud is commonly conceptualized as a 3D geometric map with the use of the Cartesian coordinates X, Y, Z. Nonetheless, this is not the appropriate point cloud conceptualization applicable in the modern field of surveying and Structural Health Monitoring. The modern point cloud, whether obtained through the use of laser scanning or image-based rendering, is multi-dimensional. In addition to the x, y, and z coordinates, the point can have additional values: RGB color, reflectance or intensity values, amplitude, return values, and timestamp.

Registration is the first crucial step in point cloud processing. It involves aligning scans performed from different viewpoints into a common coordinate system. In Terrestrial Laser Scanning, this is absolutely necessary as the scanning is stop-and-go. There are two approaches. The first is cloud-to-cloud registration. It is based on variations of the Iterative Closest Point algorithm. It aggressively shrinks the distance between overlapping point sets. It is quite useful for scanning environments on purpose. However, it is prone to errors on longer linear paths.

The second method is target-based registration, where artificial markers are installed in the scene and the coordinates are determined separately. In a geodetic and topographic respect, the advantage of the method is evident for linear structures such as bridges and viaducts. When the target points are determined using a Total Station, the positions are ascertained with millimeter accuracy on a permanent geodetic reference field. Using the method reduces the impact of error propagation and operator-dependent uncertainties related to manual and completely automatic matching. When the structures are large and error accumulation is significant, incorporating the topographic surveying solution is very dependable. Registration is followed by a process called georeferencing, which enables the transformation of a point cloud of local coordinates into a global or national reference system. Georeferencing can, for instance, involve the use of coordinates of control points or positions of scanners, which obtained their positions from a GNSS solution. Georeferencing makes sure that any virtual model produced will accurately fit into a real-world environment, allowing seamless interoperability with building information models, geographic information systems, as well as other discipline models such as building models, cadastral data, or sensors.

In NDT-based digitalization, georeferencing makes collaborative working a necessity, as well as a foundation for effective asset management.

3.1 Point cloud alignment and georeferencing

The processing of raw data into a coherent digital model is not merely a computational task but a methodological continuum that begins during the acquisition phase. A common misconception in surveying is that alignment and georeferencing are solely post-processing activities; conversely, this research posits that the reliability of the final model is strictly dictated by the topographic constraints established in situ. Therefore, the workflow adopted in this doctoral thesis moves away from the reliance on black-box automatic registration algorithms, often prone to drift in linear infrastructures, as demonstrated in the preliminary bridge case studies [32], towards a rigorous, target-based approach.

The alignment of heterogeneous datasets (LiDAR, Photogrammetry, UAV) requires a unified geometric skeleton. Before any mass-data acquisition, the survey area is materialized through a network of artificial targets (checkerboards for optical sensors and spheres for laser scanners), strategically placed to ensure visibility across multiple scan positions and flight paths. The coordinate definition of these Ground Control Points (GCPs) follows a hierarchical co-registration protocol aimed at minimizing error propagation:

1. Local precision (Total Station): first, the relative positions of the targets are measured using a high-precision Total Station (Leica FlexLine TS07). This instrument creates a rigid local network with sub-millimeter internal accuracy, essential for stitching together adjacent scans or photogrammetric blocks without introducing deformations.

2. Global Georeferencing (GNSS): subsequently, the local network is anchored to the global cartographic system (ETRS89/UTM) using a GNSS receiver (Leica Zeno GG04 Plus) connected to the RTK network. By measuring the coordinates of at least three vertices of the polygonal network, the entire rigid block is rototranslated into the absolute reference frame.

This workflow, previously tested by the author in the complex survey of historical heritage sites such as the Circus of Maxentius [33], has proven crucial for integrating NDT data into BIM and CAD (Computer Aided Design) platforms, ensuring that the digital model aligns perfectly with the real-world terrain and existing cartography [34].

For the photogrammetric datasets, the alignment utilizes the Bundle Adjustment method constrained by the measured GCPs. Scientific literature and the specific accuracy assessments conducted during this research confirm that using Total Station-measured points as constraints significantly reduces the volumetric error of the model compared to purely GNSS-assisted photogrammetry. In operational campaigns on bridge infrastructures, this approach allowed for the correction of the bowing effect often observed in linear photogrammetric strips, providing a reliable metric base even for parts of the structure inaccessible to direct contact [32].
While the preliminary tests utilized the Trimble X9, an instrument offering high speed but designed primarily for short-to-medium range applications (internal structural parts, buildings), the extensive nature of transport infrastructure necessitated a technological upgrade. To address the challenges of surveying large-scale viaducts, often characterized by piers located in inaccessible areas (e.g., riverbeds or valley floors) at significant distances from safe operator positions, the methodology was evolved to include the use of a Teledyne Optech Polaris Terrestrial Laser Scanner. Unlike the previous instrumentation, the Optech Polaris is a Long-Range Time-of-Flight (ToF) scanner capable of acquiring valid data at distances exceeding 2 km. This capability fundamentally changes the survey logistics: it allows for the acquisition of high-density geometric data of structural elements (such as high piers or distant spans) from a single safe vantage point, drastically reducing the number of setups required and, consequently, the accumulated registration error. The alignment of these long-range scans is performed in post-processing by identifying the common high-reflectivity targets surveyed by the Total Station. This ensures that the dense point cloud is not floating in space but is rigorously locked to the primary topographic network. The key technical specifications of this long-range sensor, which enable the large-scale applications detailed in the following chapters, are summarized in Table 3.1.

Once the individual datasets, TLS point clouds and photogrammetric dense clouds, are aligned to the same topographic reference frame, the final step is their integration into a unified Point Clouds. This fusion is not redundant but complementary. As demonstrated in recent studies [35, 36], reliance on a single sensor often results in incomplete datasets: TLS may leave shadow zones on the upper deck or roof elements due to its ground-based perspective, while UAV photogrammetry provides excellent coverage of these areas but may lack the geometric precision on vertical,

Table 3.1: Technical specifications of the Teledyne Optech Polaris Terrestrial Laser Scanner.

Parameter	Specification
Measurement Principle	Pulse-based Time-of-Flight (ToF)
Max Range	Up to 2000 m (at 90% reflectivity)
Range Accuracy	5 mm @ 100 m
Precision	4 mm @ 100 m
Angular Accuracy	80 μrad
Field of View (FoV)	360° (Horizontal) × 120° (Vertical)
Laser Class	Class 1 (Eye Safe)
Target Recognition	Automatic (centroid detection)
Internal Sensors	GNSS (L1 GPS + GLONASS), Compass, Inclinometer

textureless concrete surfaces.

By merging these sources within a unified coordinate system, it is possible to generate a holistic model of the infrastructure. In this integrated environment, the high geometric density of the Teledyne Optech scans (covering piers and abutments) seamlessly joins with the high-resolution textured data from the drone (covering the road surface and deck intrados). This synergistic approach eliminates blind spots and provides a complete dataset for the subsequent semantic segmentation and Scan-to-BIM processes.

3.2 Data fusion approaches

While the previous section established the geometric framework for aligning multi-source datasets, the physical integration of these clouds introduces a secondary challenge: data heterogeneity. Integrating Terrestrial Laser Scanning (TLS), which offers high-precision ranging on vertical structures, with UAV-based photogrammetry, results in a integrated point cloud characterized by varying point densities, spatial resolutions, and attribute fields. Consequently, as highlighted in recent methodological frameworks for Digital Twins, the objective of data fusion requires specific algorithmic strategies to manage the trade-off between geometric volume, informative content, and scale uniformity.

One of the most critical issues in fusing multi-sensor data is the non-uniformity of the spatial grid. TLS data typically exhibits a radial density degradation, whereas photogrammetric clouds maintain a relatively constant Ground Sampling Distance (GSD). Merging these datasets raw would result in an unbalanced model. To address this, specific resampling algorithms must be applied to achieve scale uniformity before fusion, following established integration protocols described in remote sensing literature. The workflow adopts two distinct approaches depending on the application:

- Downscaling for geometric modeling (Scan-to-BIM): when the goal is modeling macro-elements, a voxel-grid filter is applied to homogenize the cloud (e.g., 1 point per cm^3). This decimation uses a centroid-based approach to preserve the geometric mean of the surface, significantly reducing computational load without compromising the accuracy required for automated as-built modeling [37].

- Upscaling for defect analysis: conversely, in areas where sensor coverage is sparse but defect detection is critical, interpolation techniques such as Inverse Distance Weighting (IDW) are employed. This ensures that the "damage signature" (e.g., a crack) is not lost in the transition between different sensor resolutions, maintaining the high-frequency detail needed for inspection [38].

Beyond spatial coordinates, true data fusion implies the integration of radiometric attributes. The proposed workflow leverages the complementary nature of the sensors for semantic enrichment. The integrated dataset is structured to host multiple layers of information: the high-fidelity RGB values from the calibrated UAV imagery are mapped onto the precise TLS geometry. This corrects the typical exposure issues of laser scanner cameras and provides a photorealistic texture essential for visual inspection. Simultaneously, the intensity values (reflectance) from the laser scanner are preserved. This radiometric component is crucial for detecting material anomalies (e.g., moisture content) that are invisible in the visible spectrum, creating a multi-dimensional database ready for segmentation. The fusion process presented in this thesis is designed not to be a closed system but part of a broader "Multi-Scale Framework". While the core of this research focuses on the "Local Scale" (bridge level) using TLS and UAVs, the data structure is optimized to be interoperable with "Territorial Scale" data. As theorized in the Digital Twin framework developed by the author's research group [34], the high-resolution local model serves as the geometric container that can be further enriched with wide-area monitoring data, such as satellite Multi-Temporal InSAR (MT-InSAR) or decreasing-scale GIS layers. This hierarchical approach allows for a dynamic system where the static 3D survey interacts with the temporal evolution of the surrounding territory (e.g., landslide susceptibility or ground subsidence), bridging the gap between structural health monitoring and environmental risk assessment.

3.3 Pre-processing and segmentation

The transition from raw data acquisition to semantic modeling necessitates a rigorous pre-processing phase. Raw point clouds acquired in real-world scenarios inevitably contain significant noise, redundancy, and non-relevant spatial information. This is particularly evident in surveys conducted with long-range instrumentation, such as the Teledyne Optech Polaris employed in this research. While the scanner's capability to capture data at distances exceeding two kilometers is advantageous for ensuring coverage, it results in datasets populated by extraneous elements, such as surrounding vegetation, distant buildings, and terrain topography, that are immaterial to the structural analysis of the bridge.

The management of these massive datasets poses a computational challenge, as processing speed and memory usage are directly correlated with point density and scene extent. Consequently, a hierarchical cleaning strategy was adopted, refined during the author's visiting research period at the Research Unit of Photogrammetry within the Department of Geodesy and Geoinformation at Technische Universität (TU) Wien. This collaboration facilitated the implementation of advanced processing workflows leveraging the OPALS[1] (Orientation and Processing of Airborne Laser Scanning data) modular library Pfeifer (2014) [39], which allows for robust script-based automation of point cloud analysis. The necessity of comparing and selecting appropriate filtering algorithms for such complex environments is well documented in the literature by Sithole (2004) [40].

The first stage of pre-processing involves a coarse spatial filtering to define the Region of Interest (ROI). By applying a spatial crop, generally limited to a buffer of 30-50 meters around the infrastructure, the dataset size is significantly reduced, optimizing the computational load for subsequent algorithms. While initial visual inspection and manual cleaning of gross outliers can be performed in software such as CloudCompare, the systematic removal of the Digital Terrain Model (DTM) and vegetation requires an algorithmic approach to ensure repeatability and objectivity. To isolate the bridge structure from the underlying topography, a ground filtering routine was developed using the OPALS Python bindings. The methodology relies on the Robust Interpolation algorithm [41], which is particularly effective in dealing with steep terrain and variable point densities typical of terrestrial scans. Further elaborations on the implementation and accuracy of this method in laser scanning contexts are provided by Pfeifer and Mandlburger (2008) [42]. The workflow proceeds through the following steps:

- Initial surface estimation: a coarse raster surface is generated to identify candidate ground points based on local height minima.
- Iterative surface refinement: the algorithm iteratively fits a surface to the point cloud, assigning weights to points based on their vertical residuals relative to

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[1] OPALS Software: `https://opals.geo.tuwien.ac.at/html/stable/index.html`

the estimated surface. Points with large positive residuals (above the surface) are down-weighted, while points fitting the surface are classified as ground.

- Iterative surface refinement: the algorithm iteratively fits a surface to the point cloud, assigning weights to points based on their vertical residuals relative to the estimated surface. Points with large positive residuals (above the surface) are down-weighted, while points fitting the surface are classified as ground.
- Height normalization: once the DTM is established, the height of each point is normalized ($Z_{norm} = Z_{point} - Z_{DTM}$). This transformation allows for the straightforward extraction of the upper cloud (the infrastructure and vegetation) by filtering out all points where $Z_{norm} \approx 0$.

While geometric filtering effectively removes the ground, separating the structural elements from surrounding vegetation remains a challenge due to their spatial proximity. To address this, the workflow exploits the physical properties of the laser signal, specifically the return number and echo width capabilities of the full-waveform scanner. Concrete and steel structural materials are essentially non-porous materials and may provide only one clear, definitive single return echo of the laser pulse. On the other hand, vegetation is somewhat transparent to the laser beam, and thus, it usually yields numerous returns (e.g., first, intermediate, last echoes) as the pulse passes through the canopy. By filtering the dataset to retain only points characterized by a single return or specific pulse width attributes, a significant portion of the high-vegetation noise is automatically eliminated. This approach leverages the state-of-the-art in full-waveform topographic LiDAR processing described by Mallet (2009) [43].
Finally, the survey of active transportation infrastructure invariably introduces transient noise, most notably ghost points caused by vehicles or pedestrians moving through the scanner's field of view during the acquisition window (5 to 20 minutes per scan). These artifacts, which do not correspond to any physical surface, can severely impact the quality of the subsequent meshing or modeling phases. To mitigate this, a Statistical Outlier Removal (SOR) filter is applied [44]. This method computes the mean distance of each point to its k nearest neighbors; points whose mean distance deviates from the global average by more than a standard deviation threshold are classified as noise and removed.

To evaluate the effectiveness of the proposed pre-processing workflow, a specific case study was conducted on a reinforced concrete bridge located in the municipality of Zagarolo (Rome). This structure presents a particularly challenging scenario due to its integration within an urban, necessitating the removal of significant non-structural clutter, including surrounding buildings, paved courtyards, and invasive vegetation.

The acquisition campaign was executed using a TLS with a configuration of five scan positions, two external setups to capture the context and three located beneath the deck to minimize occlusions.

Figure 3.1 illustrates the raw point cloud immediately following the registration phase. The complexity of the scene is evident, with the structural elements partially obscured by environmental noise and adjacent civil structures. Following the application of the spatial and geometric filters described previously, the dataset was progressively refined. The transition from the contextualized cloud (Figure 3.2) to the fully segmented structural model (Figure 3.3) demonstrates the effectiveness of the algorithm in isolating the relevant engineering components (piers, deck, and girders) from the Digital Terrain Model and vegetation.

Furthermore, the pre-processing phase preserves the radiometric integrity of the data. Figure 3.4 highlights the point cloud visualized through intensity (reflectance) values rather than standard RGB colors. This parameter is of critical importance for the subsequent diagnostic phases, as variations in signal return intensity can serve as proxies for surface anomalies, moisture content, or material degradation, providing a diagnostic layer that complements the geometric information.

Figure 3.1: Raw point cloud of the Zagarolo bridge with in the urban context

The combination of these geometric (Robust Interpolation), radiometric (Signal Return Analysis), and statistical (SOR) filters ensures that the final point cloud represents a clean, structure-centric dataset, providing a solid foundation for the subsequent segmentation processes.

After completing the geometric and radiometric cleaning of the dataset, the next step in the process is segmentation. This step aims to break down the unstructured

Figure 3.2: Intermediate cleaning step: focus on the bridge area with residual context

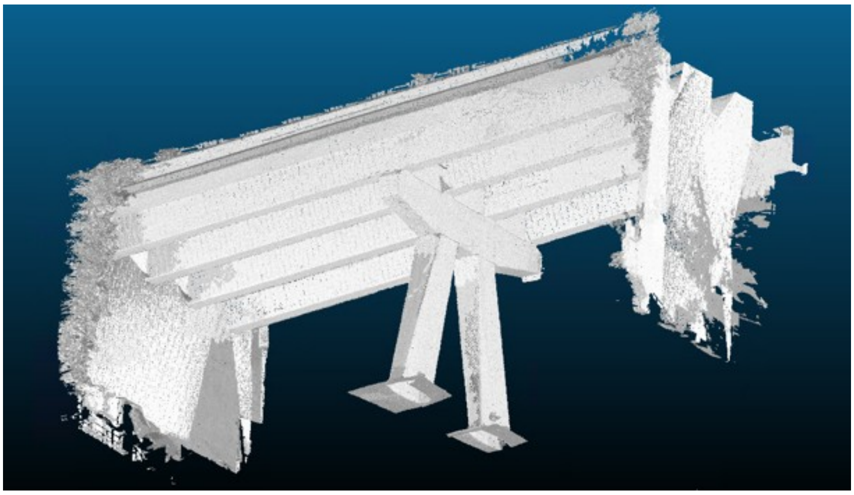


Figure 3.3: Final point cloud containing only the structural components

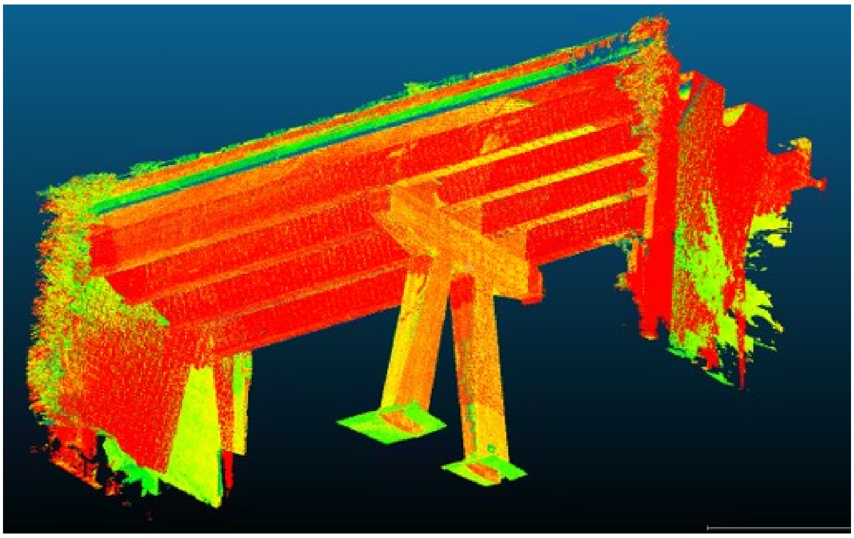


Figure 3.4: Point cloud visualization based on intensity values, highlighting surface properties for defect analysis.

point cloud into meaningful groups or segments that refer to specific structural elements, namely piers, girders, and deck slabs. However, the efficiency of semi-automated methods relies on the geometric integrity of the dataset. Before applying any clustering algorithm, it is imperative to verify that the point cloud possesses sufficient density and coverage, particularly in complex areas such as the intrados of multi-girder decks. As illustrated in Figure 3.5, incomplete data acquisition, often resulting from occlusions during the TLS survey, compromises the calculation of local geometric features. The figure highlights a scenario where the lack of points between the girders prevents the correct definition of the surfaces; the resulting normal vectors (visualized in magenta) become erratic or undefined, rendering accurate segmentation impossible. Consequently, a comprehensive data fusion strategy (as described in Chapter 3.2) is a prerequisite for this phase.

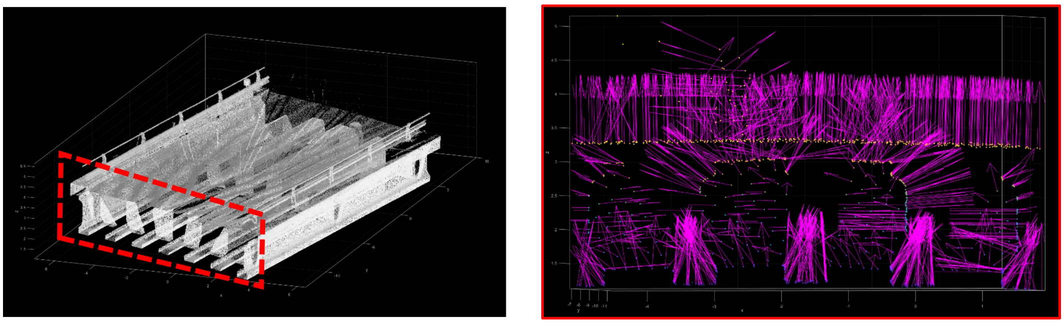


Figure 3.5: Impact of point cloud completeness on feature estimation

The fundamental descriptor for segmentation in the OPALS environment is the normal vector. The estimation of the surface normal at a query point p is typically performed by analyzing the covariance matrix of a local neighborhood of k nearest neighbors or within a fixed radius r [45]. This process involves Principal Component Analysis (PCA), where the normal vector is approximated by the eigenvector corresponding to the smallest eigenvalue of the covariance matrix [46].In this research, the opalsNormals module was employed. The selection of the neighborhood parameters is critical and was optimized for each structural typology:

- Search radius (r): a radius that is too small renders the normal estimation sensitive to surface roughness and measurement noise. Conversely, a radius that is too large tends to smooth out sharp edges (e.g., the corners of a rectangular pier), degrading the definition of structural boundaries.

- Observation strategy: for the concrete bridges analyzed in this thesis, a search radius of $5 - 10$ cm was generally adopted, balancing the need to smooth out concrete roughness while preserving the geometry of the beams.

The module was configured to store not only the normal vectors (n_x, n_y, n_z) but also the eigenvalues $(\lambda_1, \lambda_2, \lambda_3)$. These statistical measures are vital for deriving secondary features such as Planarity ($P_\lambda = (\lambda_2 - \lambda_3)/\lambda_1$) or Linearity, which serve as additional filters to distinguish flat surfaces (deck slabs) from linear features or scatter (vegetation) [47].

Once the local geometry is mathematically defined via normal vectors, the actual segmentation is executed using the opalsSegmentation module. This tool utilizes a Seeded Region Growing approach: the algorithm selects a seed point and iteratively adds neighboring points to the segment if they satisfy specific homogeneity criteria. The configuration of the segmentation parameters was tailored to the specific structural typology of the case studies:

1. Reinforced concrete bridges (girder/beam systems): for modern infrastructure composed of planar elements, the planeExtraction method was selected. This mode enforces a strict coplanarity constraint.

    - Logic: points are grouped if their distance to the adjusting plane is within a tolerance (e.g., maxDist = 0.05 m) and their normal vector deviation is minimal (e.g., maxSigma).
    - Application: this approach effectively separates adjacent girders. Since each beam face represents a distinct plane with a specific normal orientation, the algorithm creates individual segments for each web and flange, facilitating the subsequent modeling of discrete BIM objects.

2. Masonry arch bridges: for historical structures characterized by curved geometries (e.g., barrel vaults or arches), the planar assumption is invalid. In these cases, the generic condClustering (Conditional Clustering) method was applied [48].

    - Logic: instead of fitting a plane, the homogeneity criterion is defined by the smoothness of the normal vectors. A custom criterion string (e.g., dot(n, n[0]) > 0.95) ensures that points are grouped as long as the surface curvature changes gradually.
    - Application: this allows the segmentation of a continuous vaulted surface as a single entity, avoiding the over-segmentation that would occur if a planar algorithm attempted to approximate an arch with multiple small planes.

By adapting the segmentation logic, rigid plane extraction for concrete vs. smooth region growing for masonry, the methodology ensures that the resulting point clusters are semantically significant, directly corresponding to the structural components required for the creation of the BIM Model.

The practical implementation of this methodology is exemplified through the processing of a masonry arch bridge dataset, previously cleaned of vegetation and non-structural artifacts. The application of the condClustering algorithm, tailored with the curvature-based criteria described above, yields a semantically segmented point cloud where distinct structural macro-elements are automatically identified and classified via the SegmentID attribute.

As illustrated in Figure 3.6, the segmentation process successfully differentiates the vertical support structures. The algorithm assigns unique IDentifiers (IDs) to the coherent surfaces of the piers. Although a single pier may be composed of multiple segmented faces (e.g., frontal and lateral planes), the semantic differentiation allows for the rapid isolation of each pier from the adjacent ones and from the superstructure. This granular separation is critical for masonry assessments, where the analysis of plumbness or deformation must be performed on a pier-by-pier basis.

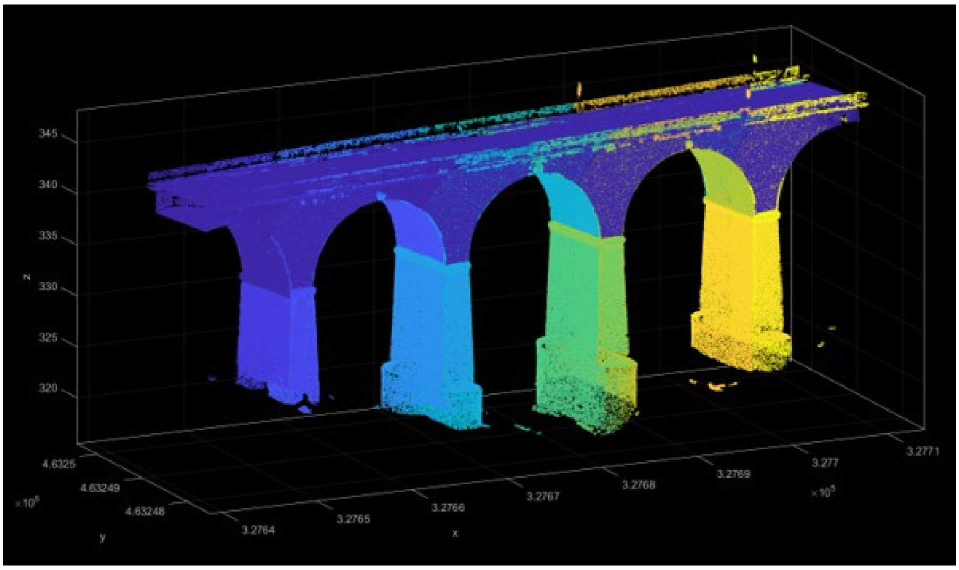


Figure 3.6: Global segmentation results

Furthermore, the flexibility of the segmentation logic, specifically the ability to handle gradual changes in normal vector orientation, proves particularly effective for the longitudinal elements. Figure 3.7 demonstrates the extraction of the spandrel walls and the upper parapets. Unlike planar extraction methods which would fragment these irregular masonry surfaces into disjointed tiles, the conditional clustering treats the entire spandrel wall as a continuous geometric entity. This holistic segmentation significantly reduces the complexity of the dataset, transforming millions of raw points into a manageable set of semantic objects.

The true value of this pre-processing phase becomes evident during the extraction of specific structural typologies. By filtering the dataset based on the generated SegmentID, it is possible to isolate complex geometries such as the barrel vaults of the arches. Figure 3.8 depicts the result of this query, showing the clean extraction of

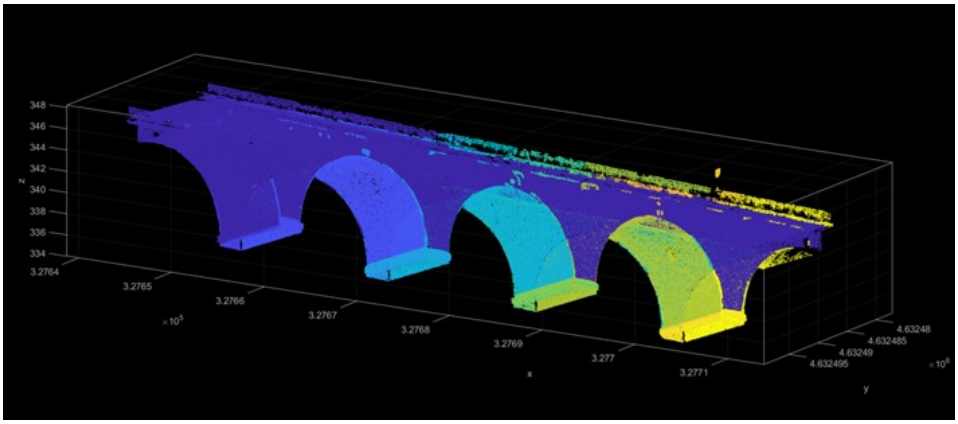


Figure 3.7: Detailed segmentation of longitudinal elements

the intrados surfaces. This isolation is a prerequisite for advanced structural analysis, as it allows for the precise mapping of surface deviations relative to the ideal arch geometry without interference from the piers or the roadway above.

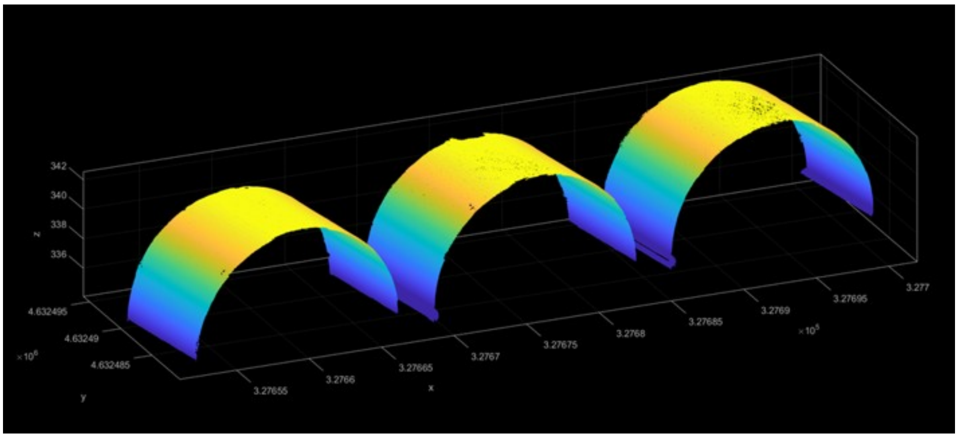


Figure 3.8: Isolation of the barrel vaults (arches) through SegmentID filtering

The transition from a raw, unstructured point cloud to a segmented, object-oriented dataset represents a paradigm shift in the Scan-to-BIM workflow. Traditionally, modeling involved the manual tracing of 3D geometries over the point cloud, a labor-intensive and error-prone process. However, the availability of pre-segmented surfaces, as shown in Figure 3.9 where the planar faces of the piers are clearly delineated, enables the adoption of automated reconstruction strategies.

Literature in the field of computer vision and photogrammetry supports this approach, highlighting how segmented data facilitates the application of shape detection algorithms. Methods such as the RANSAC (Random Sample Consensus) paradigm [49] or Poisson surface reconstruction [50] can be applied directly to these segments to mathematically fit geometric primitives (planes, cylinders, cones) to the noisy data. As noted by Tang (2010) [51] and more recently by Bassier (2017) [52], the semantic segmentation of the point cloud is the bottleneck that, once resolved, allows for the algorithmic generation of B-Rep (Boundary Representation) models.

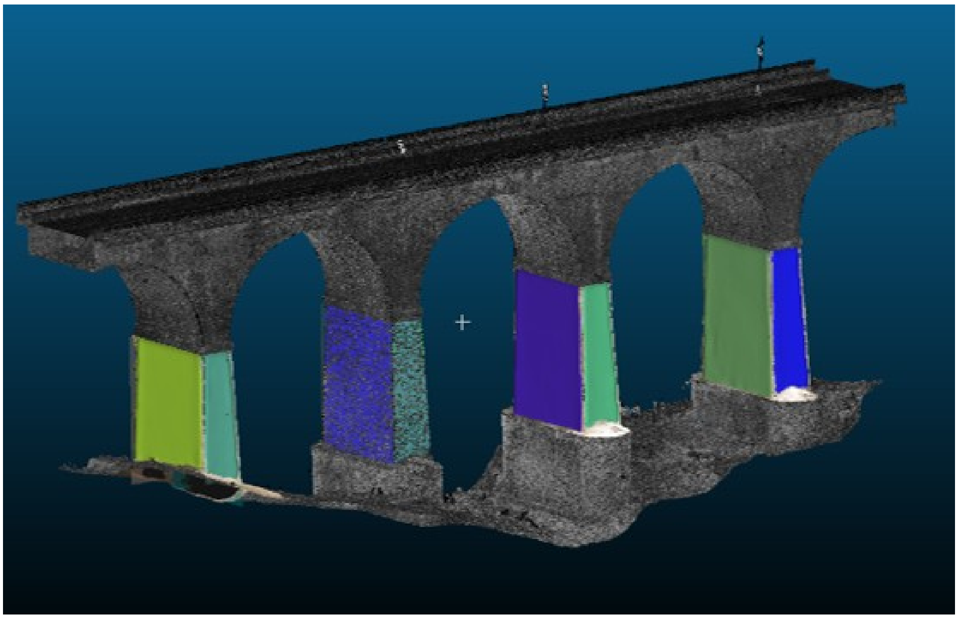


Figure 3.9: Identification of planar primitives on the bridge piers

Consequently, the workflow proposed in this thesis moves beyond mere visualization. By converting the point cloud into a database of geometric properties (normal vectors, curvature, segment connectivity), it lays the groundwork for the Parametric Scan-to-BIM process. The following chapters will detail how these segmented clusters are utilized to inform the creation of adaptive BIM families, where the geometry is not just drawn, but mathematically derived from the experimental reality of the survey.

3.4 Defect recognition from point clouds

From an infrastructure engineering perspective, defect recognition is primarily aimed at supporting asset management and maintenance planning rather than detailed structural verification. In this context, point clouds provide not only geometric information but also valuable radiometric cues that can reveal early-stage pathologies [53, 54]. A promising approach involves the analysis of reflectance or intensity values recorded by laser scanners. These values depend on the strength of the laser return and are affected by the material characteristics, surface roughness, angle of incidence, and ambient environment [55]. Since water absorbs infrared radiation, moisture results in a lower return intensity, appearing as dark areas in the intensity rendering. Similarly, material variations and vegetation growth can be distinguished from sound concrete [12].

Through the detailed analysis of spatial characteristics and anomalies within the acquired data, it is possible to identify regions susceptible to moisture ingress, material degradation, or biological colonization. Research within the field of Structural

Health Monitoring (SHM) has increasingly emphasized the diagnostic capabilities of radiometric analysis, particularly when synergistic with geometric parameters. Notably, [56] demonstrated the efficacy of utilizing TLS intensity data combined with unsupervised classification algorithms to characterize pathologies, such as moisture content and material weathering, in historical structures. Complementarily, [57] proposed a semi-automated methodology that integrates radiometric segmentation with 3D geometric models, establishing a robust framework for monitoring the temporal evolution of surface degradation. The use of radiometric parameters within the digital model promotes the transition from descriptive analysis to assessment. When implemented as part of a BIM or Digital Twin structure, such data form the basis for informed decision-making on maintenance interventions, which become possible even before the occurrence of structural failure. In this respect, the identification of defects in point clouds represents a critical aspect of digitalization in NDT [58].

The methodology adopted in this research moves away from fully supervised classification strategies, which require extensive labeled datasets often unavailable for specific infrastructure contexts. Instead, it focuses on unsupervised anomaly detection via clustering algorithms. The core objective is not to immediately semantically label a defect (e.g., distinguishing between spalling and delamination), but to mathematically extract clusters of points that exhibit anomalous behavior relative to their local neighborhood. The process relies on the assumption that sound structural elements (e.g., concrete piers, decks) exhibit homogeneous geometric and radiometric features. Therefore, defects appear as statistical outliers or distinct clusters within the multi-dimensional feature space of the point cloud.

To operationalize this feature extraction and clustering, the raw point cloud $\mathcal{P} = \{p_1, \ldots, p_n\}$ is enriched with a feature vector for each point p_i. While traditional geometric surveys rely solely on spatial coordinates (x, y, z), this methodology integrates the intensity value I and, where necessary, the local normal vector $\mathbf{n}$. The feature vector v_i for a generic point is defined as:

$$v_i = [x, y, z, I, n_x, n_y, n_z] \tag{3.1}$$

A K-Means clustering algorithm is then applied to partition the point cloud into k sets (clusters) $S = \{S_1, S_2, \ldots, S_k\}$ so as to minimize the within-cluster sum of squares (WCSS). The algorithm iteratively assigns points to the nearest centroid μ_j based on Euclidean distance in the feature space:

$$\arg\min_S \sum_{i=1}^{k} \sum_{p \in S_i} ||v_p - \mu_i||^2 \tag{3.2}$$

In the context of bridge inspection, this effectively separates the point cloud into "background" (sound concrete) and "foreground" (anomalies). For instance, areas with high surface roughness or altered reflectance due to humidity will cluster together, separating themselves from the surrounding smooth, dry concrete. This allows for the automatic extraction of the Region Of Interest (ROI) without manual segmentation.

Once the anomalous clusters are identified, the subsequent challenge is converting these dispersed sets of points into manageable digital objects compatible with BIM environments [51]. A raw cluster of points is insufficient for Asset Management platforms, which require defined geometric entities to associate with metadata (e.g., severity, date of detection).

The proposed workflow involves a geometrization process where the isolated point clusters are converted into closed mesh surfaces or bounding volumes. Since the original point cloud is georeferenced, the resulting geometric objects maintain their absolute spatial position. This process involves:

- Cluster isolation: the points belonging to the "defect" cluster are extracted as a separate entity.
- Mesh generation: a surface reconstruction algorithm (e.g., Poisson reconstruction or Delaunay triangulation) is applied to the extracted points to generate a watertight mesh. This creates a volumetric representation of the defect.
- BIM integration: the generated mesh is imported into the BIM authoring software (e.g., via interoperability scripts using visual programming languages like Dynamo).

This procedure ensures that the defect is no longer just a visual texture on a 3D model but a distinct BIM object. Being a discrete object, it can be populated with specific parameters such as the degradation level derived from the intensity analysis, the surface area calculated from the mesh, and the risk classification defined by current guidelines. This transition from points to semantic objects is the enabler for the NDT-driven Digital Twin, where the geometry of the defect is inextricably linked to its diagnostic data.

To conclude, the entire data processing chain detailed in this chapter, from the target-based registration of raw scans to the unsupervised clustering of radiometric anomalies, is summarized in the workflow diagram presented in Figure 3.10. This diagram describes the logical sequence of the proposed methodology: the process begins with the fusion of the data from TLS and UAV to create the metric space, and it continues with two streams of analysis running side by side: Geometric Segmentation, where the focus is on the extraction of geometric data (planes and regions), and Defect Recognition, where the target is the isolation of the radiometric defects. The two streams of information combine to create the semantic BIM Model, where the model is not only geometric but also diagnosis-capable.

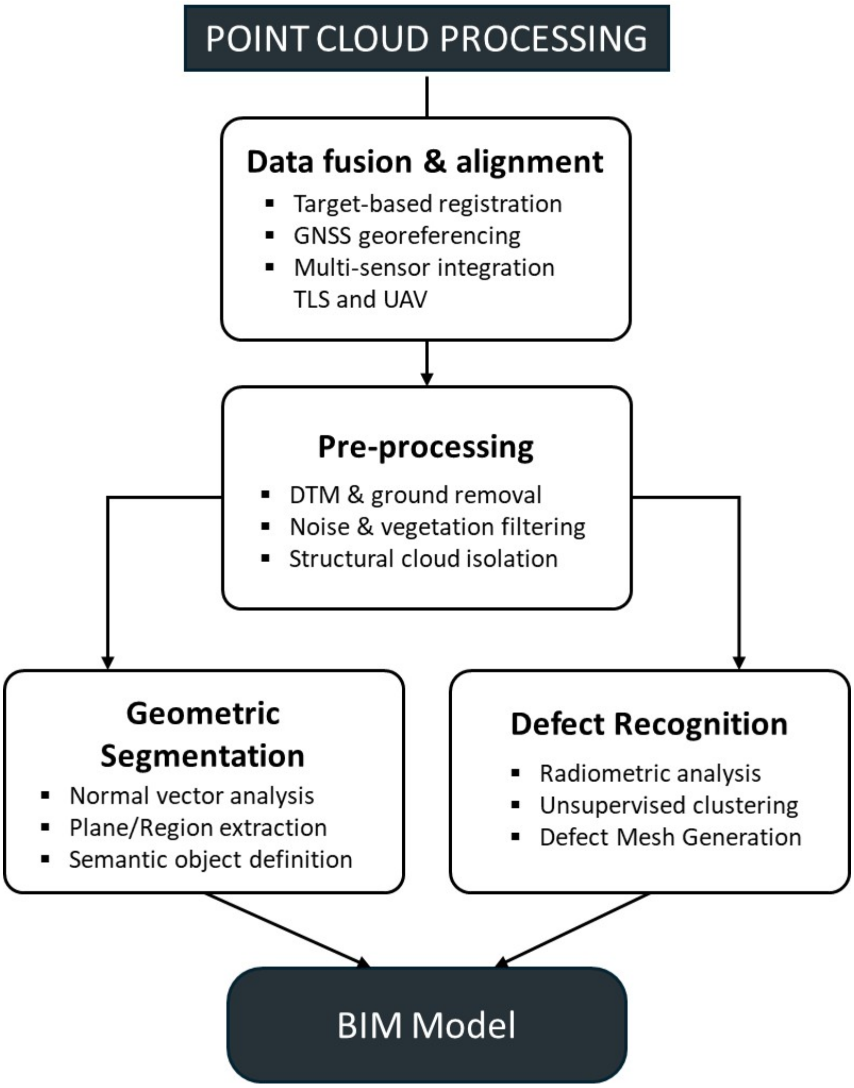


Figure 3.10: Comprehensive workflow of the proposed methodology: from multi-source data fusion to semantic BIM generation

Chapter 4

From point cloud to digital models

Following the acquisition and processing of point cloud data described in Chapter 3, the subsequent phase involves the conversion of these raw geometric datasets into semantic digital models, a process widely known as "Scan-to-BIM". While traditional modeling approaches often involve the manual tracing of point clouds, a time consuming process that essentially relies on the user's visual interpretation to digitally reconstruct the structure over the scan data, the methodology proposed in this research adopts a semi-automated, object-oriented approach.

Rather than modeling every unique irregularity of the raw scan, this workflow prioritizes the use of parametric and adaptive families. This approach allows for the rapid generation of digital models that are geometrically consistent with the surveyed data while maintaining the intelligent structure required for a BIM database. The process relies on the preparation of the point cloud data, segmented into structural components (as detailed in the previous chapter), which then serve as the geometric reference for placing intelligent BIM objects. By utilizing pre-defined parametric families for structural components, such as decks, piers, and abutments, it is possible to standardize the modeling process, ensuring that the resulting models are not only visually accurate but also structurally and semantically coherent.

4.1 Creation of parametric and adaptive families

The core of the proposed Scan-to-BIM workflow lies in the development of a comprehensive library of parametric families capable of adapting to the specific geometric constraints identified during the survey phase. The modeling environment selected for this research exploits the interoperability between Autodesk Civil 3D and Autodesk Revit. Specifically, Civil 3D is utilized for the definition of the road infrastructure's geometry (alignment and profile), while Revit is employed for the detailed structural modeling due to its robust parametric capabilities. Although these specific software packages are used here, the underlying methodological principles remain applicable to other BIM authoring tools.

For the linear components of the infrastructure, particularly the bridge deck, the methodology employs "Adaptive Families" (Figure 4.1). Unlike standard families, which are typically anchored to a single insertion point, adaptive families are driven by multiple insertion points. This fundamental difference allows the geometry to deform and align itself along complex paths, a critical feature for infrastructure that follows curvilinear alignments.

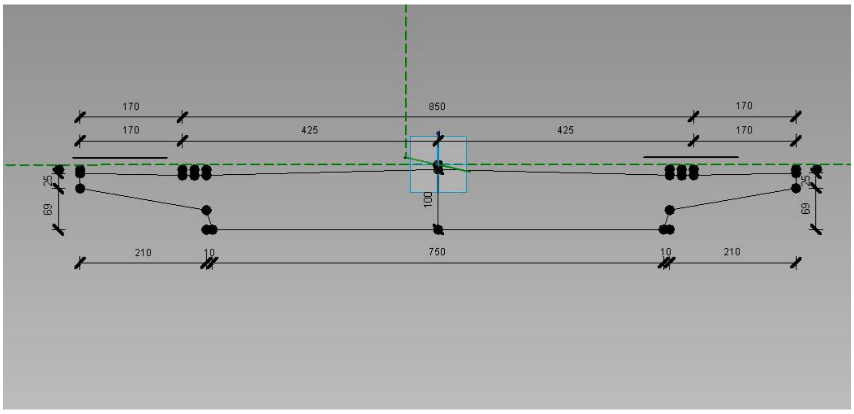


Figure 4.1: Adaptive families - bridge deck

The geometric definition begins within the Civil 3D environment, where the road axis is reconstructed in terms of planimetry (horizontal alignment) and altimetry (vertical profile). This accurate reconstruction of the road centerline provides the necessary spatial reference curves. These curves transmit the essential geometric data required to generate the deck within the Revit environment. The modeling process for the deck proceeds as follows:

- Typological definition: the deck is modeled starting from a 2D typological cross-section (e.g., a box girder, slab, or beam section).

- Parametric instantiation: key dimensional attributes, such as deck width, beam height, and slab thickness, are defined as instance parameters. This allows for the adjustment of the cross-section for each specific span based on the measurements derived from the database or the point cloud.

- Extrusion along alignment: the 3D geometry is generated by extruding this parameterized section along the reference curve derived from the Civil 3D re-design. By utilizing adaptive points to control the start, middle, and end of the span, the model automatically conforms to the curvilinear alignment and superelevation of the road axis, ensuring geometric consistency with the Laser Scanner survey.

For the vertical supporting elements, specific parametric families were developed for both abutments and piers, designed to interact with the segmented point cloud data processed in Chapter 3.

- Abutments: a generic abutment family was modeled, comprising the foundation, wing walls, and the stem (Figure 4.2). To ensure precise positioning relative to the road axis, the family logic relies on two adaptive points:
  - Insertion point: defines the spatial location (x, y, z).
  - Orientation vector: defines the directional rotation, ensuring the abutment is perpendicular to the bridge axis or skewed according to the specific design. Crucially, the dimensional parameters for the abutment, specifically the length, width, and depth of the wing walls, are not arbitrary. They are populated using the numerical values directly extracted from the segmentation of the point clouds performed in the previous phase.

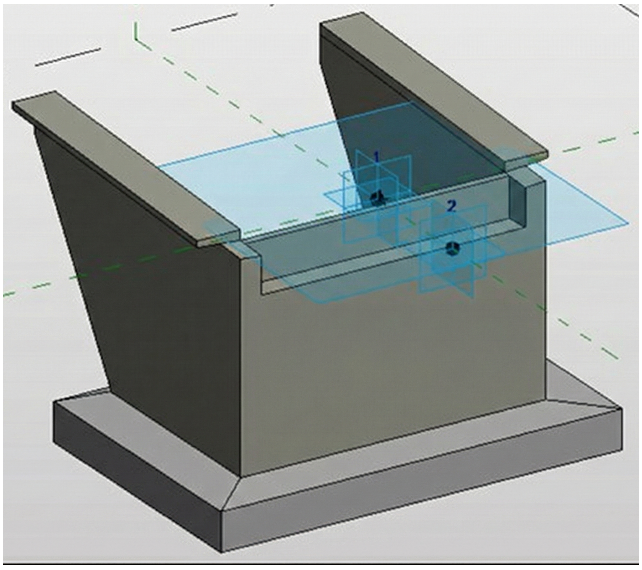


Figure 4.2: Adaptive families - abutment

- Piers: similar to the abutments, the key geometric properties, such as column height and cross-section dimensions, are fully parameterized (Figure 4.3). Following a review of the state of the art regarding the Italian infrastructure heritage, a library of families was created to cover the most recurrent pier typologies (e.g., circular, rectangular, multi-column bents) (Figure 4.4). This allows for rapid modification based on the specific survey data for each individual pier.

Information management and Level of Detail (LOD) to transform these 3D geometries into true information containers, Shared Parameters are established within

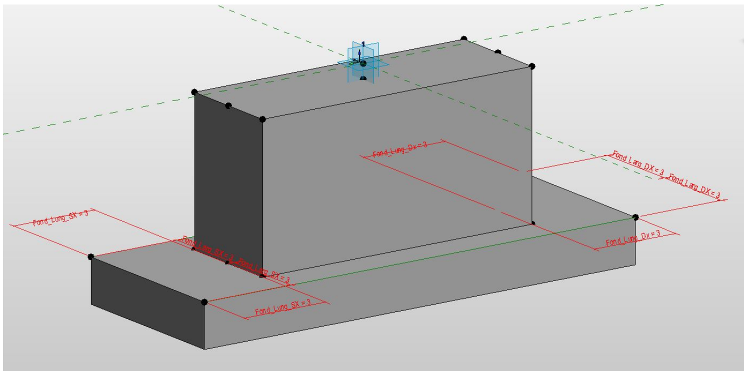


Figure 4.3: Adaptive families - piers

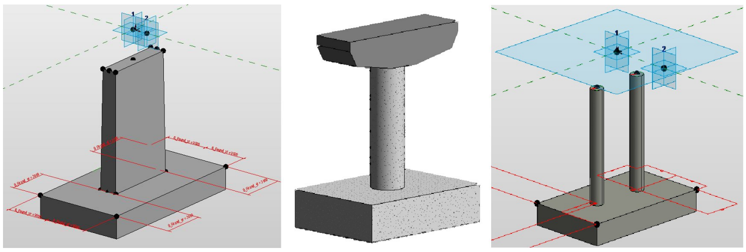


Figure 4.4: Adaptive families - different types of piers

the families. These parameters correspond directly to the data fields present in the infrastructure database (e.g., Structure ID, Material, Census Date). Through the linking of these common parameters to the geometry, the model is designed to automatically capture and store the metadata that is non-geometric in nature, hence promoting interoperability. In particular, it is necessary to point out that the process illustrated in the above definition triangulates a basic geometric representation, usually between LOD D and E, depending on the part. This level of detail is sufficient for general purposes. However, in particular cases of structural analyses requiring a higher level of detail, such as in the representation of local damage or non-standard joints, this process allows a gradual refinement of these families to a higher LOD, without renouncing the parametric system.

4.2 Creation of BIM models from point cloud data

Once the library of adaptive and parametric families is established, the reconstruction of the digital model is significantly accelerated through the application of visual programming algorithms. The tool used for this is the Autodesk Dynamo, and this tool is based on the visual programming interface and the computational processing of the Revit environment. The main role of the Dynamo tool is the necessary connection, based on the survey data, as well as the Building Information Modeling tool. The developed script is organized into distinct logical groups, designed to process data sequentially. As illustrated in the workflow diagram (Figure 4.5), the algorithm proceeds through specific nodes that govern the data ingestion, processing, and element instantiation:

1. Data ingestion and georeferencing (Civil 3D integration): the initial block of the script (located at the top-left of the visual graph) is dedicated to retrieving geospatial data. It interfaces directly with the Civil 3D outputs to import the absolute coordinates of the road axis and the georeferenced position of the bridge structure. This step ensures that the resulting BIM model is spatially correct and aligned with the national coordinate system used during the survey.

2. Deck modeling and encoding: the data flow then moves to the first processing group, which handles the superstructure. The script reads the coordinates for the start, mid-point, and end-point of each span. It instantiates the adaptive deck family by driving the adaptive points to these coordinates, ensuring the 3D extrusion strictly follows the curvilinear alignment derived from the track axis (Figure 4.6). Simultaneously, the script performs an encoding routine, automatically assigning the relevant identification codes and metadata to the deck elements.

3. Abutment instantiation: the second logical group manages the bridge extremities. The script utilizes the coordinates of the bridge heads to place the parametric abutment families. It automatically calculates and applies the necessary rotation vectors to align the abutments perpendicular to the road axis (or at the specific skew angle detected). Dimensional parameters for the wing walls are populated at this stage based on the as built data (Figure 4.7).

4. Pier generation: the final group addresses the substructure. The algorithm iterates through the list of identified pier locations. For each instance, it selects the appropriate family type (e.g., circular, rectangular) and adjusts the height parameter based on the segmented point cloud data (Figure 4.8). As with the other elements, each pier is simultaneously coded with its unique structure ID.

A key advantage of this algorithmic approach is the intrinsic georeferencing of components. Since every element, deck, abutment, and pier, is generated based on absolute coordinates, they automatically align within the 3D space to form a unified, coherent model without the need for manual assembly (Figure 4.9). Post-generation, the validity of the BIM model is assessed by superimposing it over the original point cloud (Figure 4.10). This visual comparison confirms the geometric fidelity of the reconstruction, demonstrating that the digital model accurately reflects the as-built infrastructure.

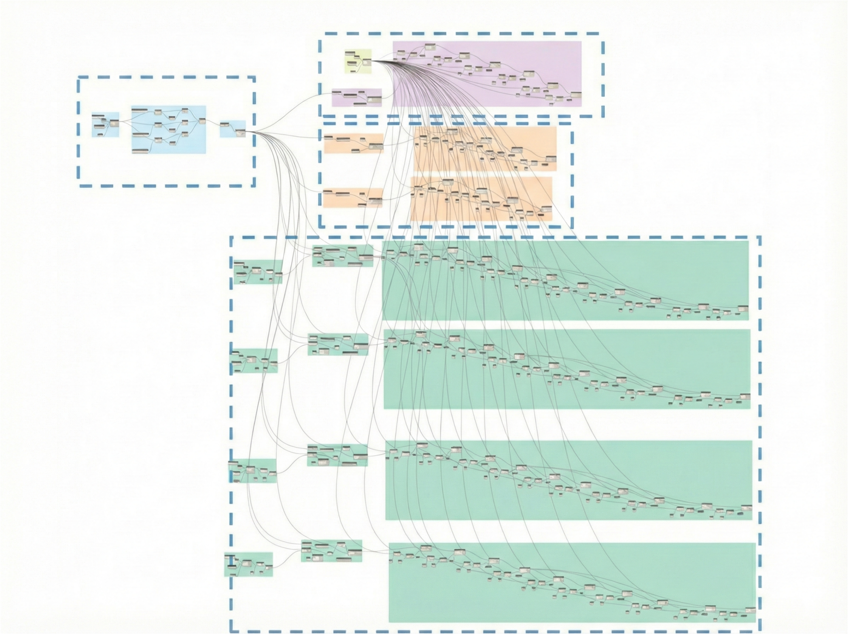


Figure 4.5: Dynamo - visual programming

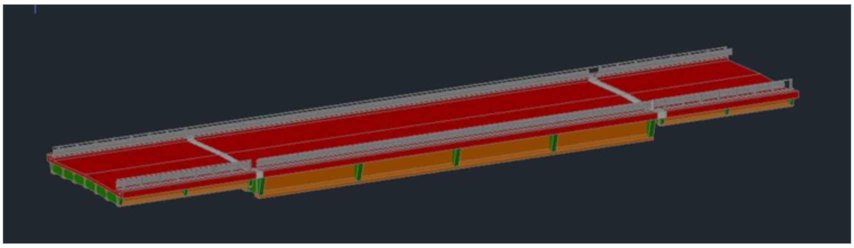


Figure 4.6: BIM model of upperstructure

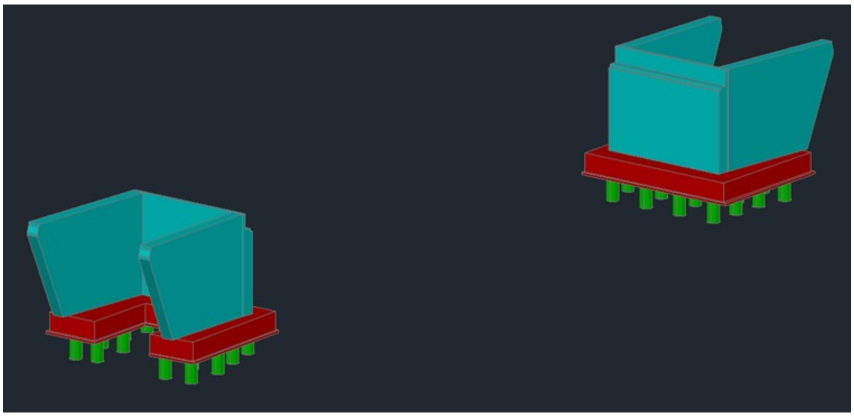


Figure 4.7: BIM model of abutment

Figure 4.8: BIM model of the pier

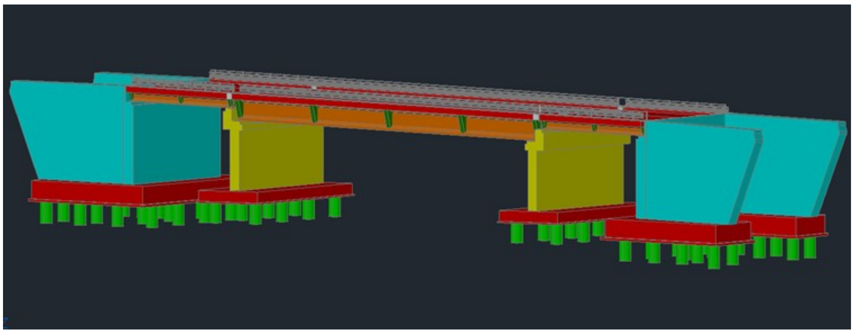


Figure 4.9: Complete BIM digital model

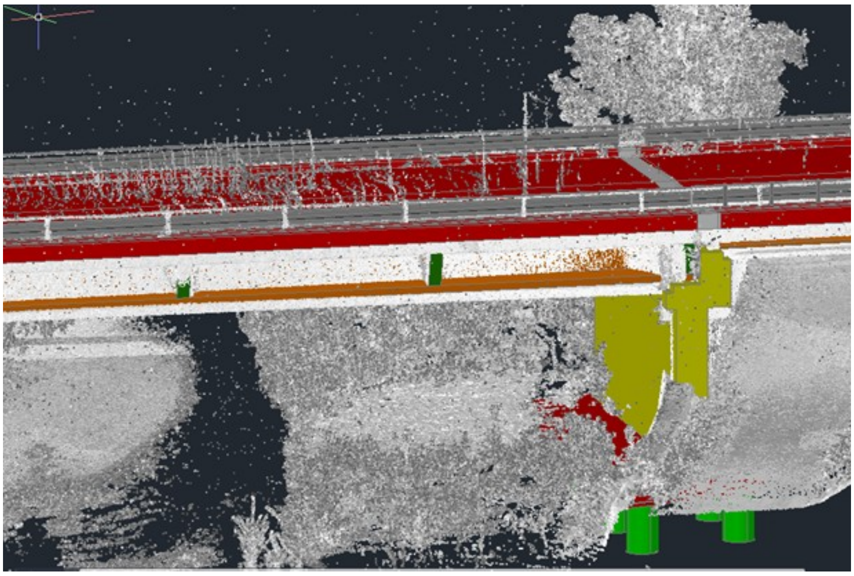


Figure 4.10: Comparison between the point cloud and the BIM model

4.2.1 Assignment of metadata of BIM elements

While the geometric reconstruction described in the previous sections constitutes the visual foundation of the digital model, the paradigmatic value of Building Information Modeling lies fundamentally in the "Information" component. A geometric model, no matter how accurate, remains a static representation if devoid of semantic data. Therefore, the subsequent phase of this research involves the transformation of the 3D model into a dynamic relational database, capable of supporting the asset management lifecycle, specifically inspection and maintenance activities. The discretization of the bridge into individual parametric components, piers, abutments, and deck spans, was not merely a geometric convenience but a strategic choice to facilitate granular data management. Unlike traditional CAD drawings where information is generic or attached to layers, the proposed BIM methodology allows for specific metadata to be assigned to each unique structural element.

To operationalize this, the system utilizes shared parameters. These are custom data fields defined within the BIM authoring software (Revit) that act as containers for specific types of information. By adhering to the taxonomy proposed by recent literature and the requirements of the Guidelines for Risk Classification and Management of Existing Bridges (M.D. 578/2020) [3], the information structure is categorized into three distinct levels:

1. Identity and registry data: this includes static information such as the unique structure IDentifier (ID), construction year, material properties (e.g., concrete strength class, steel reinforcement grade), and geometric constraints derived from the survey.

2. Inspection history: the model is designed to store temporal data regarding inspection activities. Parameters are created to log the date of last inspection, the inspector ID, and the next scheduled inspection. This transforms the BIM model into a living archive of the structure's history.

3. Defect and condition state: crucially, parameters are established to record the condition of the element. Following the defect catalogs outlined in the Guidelines, specific fields allow the inspector to input the type of defect (e.g., spalling, corrosion, leaching), its severity (K_1), and its extent (K_2).

4.2.2 Defect integration in BIM

The integration of these parameters elevates the model from a passive data repository to an active Decision Support System (DSS). By embedding the defect parameters directly into the structural elements, the model can be programmed to perform intrinsic calculations. For instance, by inputting the defect values identified during an inspection, the system can automatically compute the local Defect Level for a specific pier or span. This capability allows the model to function as an alert system. Through color-coded visualization filters (View Templates), elements can be automatically highlighted in red, yellow, or green based on their calculated risk value. This immediate visual feedback enables Asset Managers to instantly identify critical components requiring urgent maintenance or in-depth monitoring, streamlining the prioritization of interventions.

However, assigning alphanumeric metadata to a generic structural element represents only one dimension of the Digital Twin's potential. To achieve a truly high-fidelity representation of the asset's health, it is necessary to integrate the morphological representation of the degradation itself. This research proposes a workflow to transition from the 2D identification of anomalies (performed in Chapter 3 via reflectance analysis) to their 3D volumetric integration within the BIM environment.

As detailed in Section 3.4, the processing of intensity values allowed for the segmentation of the point cloud, isolating clusters of points characterized by anomalous reflectance behaviors compared to the surrounding healthy material. While these clusters identify the presence of a potential defect, their integration into the BIM process requires a conversion from a discrete set of points to a continuous surface (Figure 4.11).

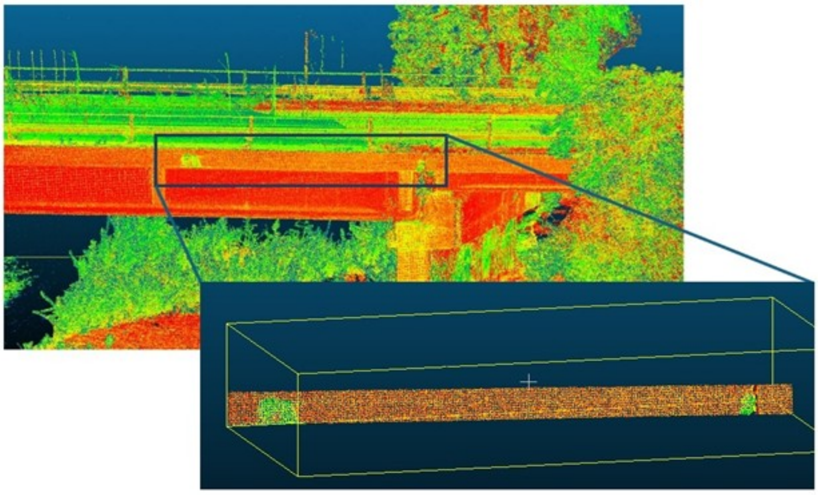


Figure 4.11: Filtered point clouds with anomalous intensity values

The workflow adopted involves isolating the Region of Interest (ROI) around the identified anomaly. Within this subset, specific filtering algorithms are applied to remove noise, followed by a clustering process (e.g., Euclidean clustering) to define the boundaries of the damage. These isolated point clusters are then triangulated to generate a 3D Mesh (Figure 4.12). This mesh does not merely represent a visual texture but constitutes a measurable geometric object capable of providing quantitative data regarding the extent, width, and depth of the anomaly.

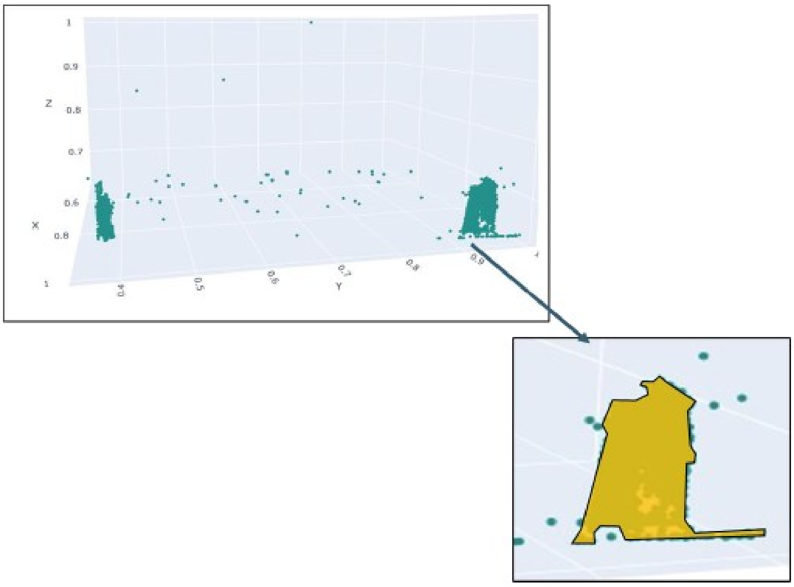


Figure 4.12: Creation of the geometric mesh

Once generated, these meshes are imported into the BIM authoring environment as distinct Generic Model families or specialized "Defect Families". These objects are then geometrically attached to the host structural element (e.g., the pier or the deck soffit). This operation allows for a precise spatial localization of the degradation, enabling the inspector to visualize not just which element is damaged, but where exactly the damage is located and its volumetric magnitude.

The reliability of this NDT-driven digital inspection method was rigorously demonstrated through field operations conducted within the framework of the "MLazio" research project. The primary objective was to verify whether the radiometric anomalies detected by the TLS and modeled in the BIM environment corresponded to actual material degradation visible to the human eye. To perform this ground-truth verification, a specialized by-bridge inspection platform was employed. The comparison between the digital model and the physical inspection yielded significant results. The regions marked high intensity anomalies on the points cloud always correlated with observable signs of distress and included moisture retention.

Therefore, the methodology shows that the process of Scan-to-BIM can enable the development of a preventive diagnosis tool. The process consists of the execution of a “digital pre-inspection” on the enhanced model, which allows the inspectors to plan their visits on-site prior to the detection of the critical areas, thus optimizing the execution time on-site.

4.3 Interoperability and IFC export

To ensure the longevity and accessibility of the data beyond the design phase, the final step in the workflow is the export of the enriched model to an open standard format. Reliance on proprietary file formats creates significant barriers to collaboration and long-term archiving, a limitation that is particularly detrimental to the management of public infrastructure where data persistence is required for decades. Consequently, the model is mapped and exported to the Industry Foundation Classes (IFC) format, strictly adhering to international standards such as ISO 16739:2020 [59].

The adoption of the IFC standard (specifically the IFC 4x3 schema extensions for infrastructure) allows for the articulation of the BIM model through a rigorous spatial hierarchy. This tree-like structure organizes the physical components of the bridge according to logical management criteria, tailored to the specific use case. As illustrated in Figure 4.13, the spatial decomposition follows a multi-level hierarchy:

- Level 1: IfcSite. The root of the spatial structure is represented by IfcSite. This entity defines the specific territory and environmental context in which the infrastructure is located, effectively acting as the container for the georeferenced coordinates derived from the Model Builder in Infraworks or the initial survey data.

- Level 2: IfcFacility. The second level of decomposition introduces the semantic differentiation of the asset type. The IfcFacility entity generalizes the built asset, which is then specialized into domains such as IfcBuilding, IfcRoad, IfcRailway, or, in this specific case study, IfcBridge. Correctly identifying the asset class at this level is fundamental for establishing valid interactions between different infrastructure domains (e.g., a road crossing a bridge).

- Level 3: IfcFacilityPart. The third level concerns the functional decomposition of the bridge. Through the IfcFacilityPart entity, the asset is segmented into macro-components, specifically the Substructure (IfcSubstructure) and the Superstructure (IfcSuperstructure).

- Level 4: IfcObject. Finally, the hierarchical nodes are populated by the physical elements themselves. A facility part, such as the substructure, acts as a container for the specific components modeled in the previous steps, such as the deck (IfcDeck or IfcSlab), abutments (IfcAbutment), and piers (IfcColumn or IfcPier).

During the export process, the internal "Shared Parameters" defined in the authoring software are mapped to standard IFC Property Sets (e.g., Pset_Condition, Pset_MaintenanceTrigger). This ensures that the semantic richness, including inspection dates, material data, and calculated risk values, is strictly preserved and transferred alongside the geometry. The resulting IFC file serves as a vendor-neutral deliverable that allows for agile data sharing across disparate databases and provides the necessary input for the subsequent virtualization phases in 3D visualization engine (Unity).

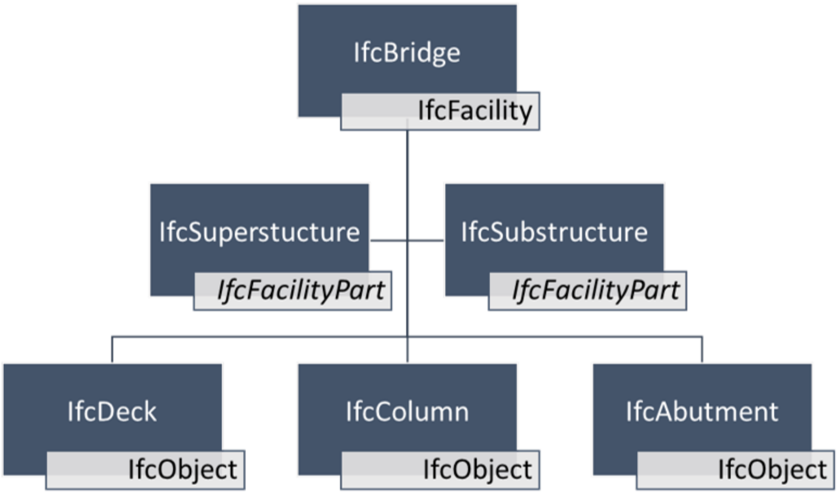


Figure 4.13: Structure of IFC Bridge

4.4 Beyond BIM: virtual and interactive models

The evolution of digital documentation in civil engineering is increasingly moving towards the integration of static informative models into dynamic, interactive environments. While the definition of a BIM model or a high-density point cloud represents a fundamental step for asset digitization, the static nature of these deliverables often limits the immediate accessibility and interpretability of the data for stakeholders who may not be proficient in specific BIM authoring software. To address this limitation, this research explores the transition from standard modeling environments to Virtual Reality (VR) and interactive platforms, specifically leveraging real-time rendering engine (Unity). In the context of this doctoral work, the digitization workflow was extended by importing the reconstructed models into Unity Platform, a cross-platform advanced graphics engine developed by Unity Technologies. Although primarily conceived for video game development, Unity has gained widespread adoption in the Architecture, Engineering, and Construction (AEC) industry due to its capability to handle complex three-dimensional environments, advanced physics simulations, and real-time rendering. As extensively explored in the research activities conducted by the Department, particularly regarding the support of BIM for driving simulation procedures, technologies originally designed for gaming offer robust solutions for infrastructure management. Unity acts as a versatile data aggregator, characterized by its high interoperability with industry-standard 3D formats. Specifically, the platform facilitates the seamless ingestion of Wavefront OBJ and Filmbox (FBX) files. These are used as an interface between the survey processing software (such as Agisoft Metashape) and the interactive platform. Furthermore, there is widespread support for the FBX format among leading BIM authoring software applications, which makes it relatively easy to import parametric models alongside the photogrammetric meshes. This allows for the creation of a complex scene that strives to find a balance between visual fidelity and data productivity (Figure 4.14).

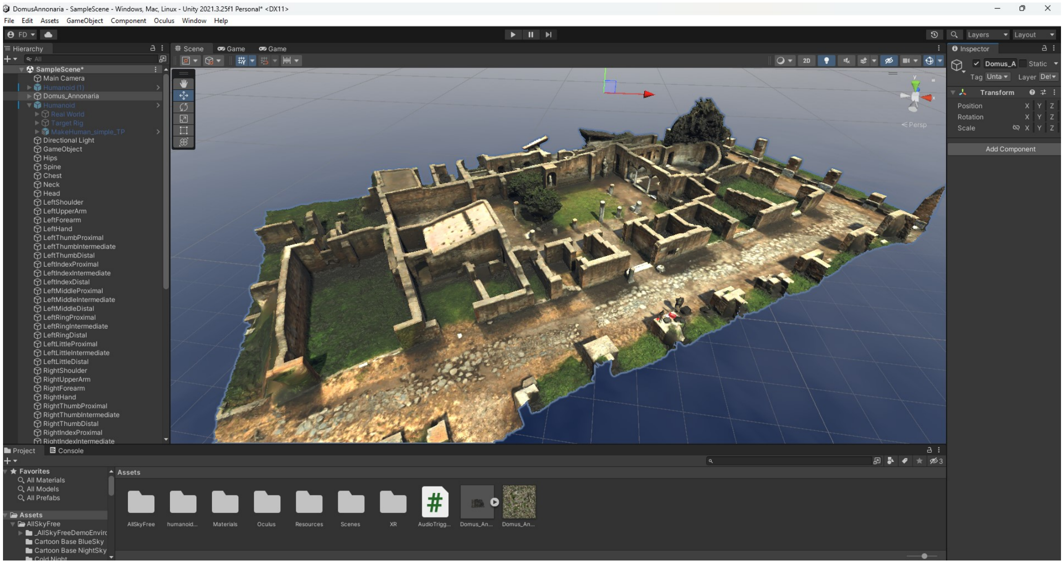
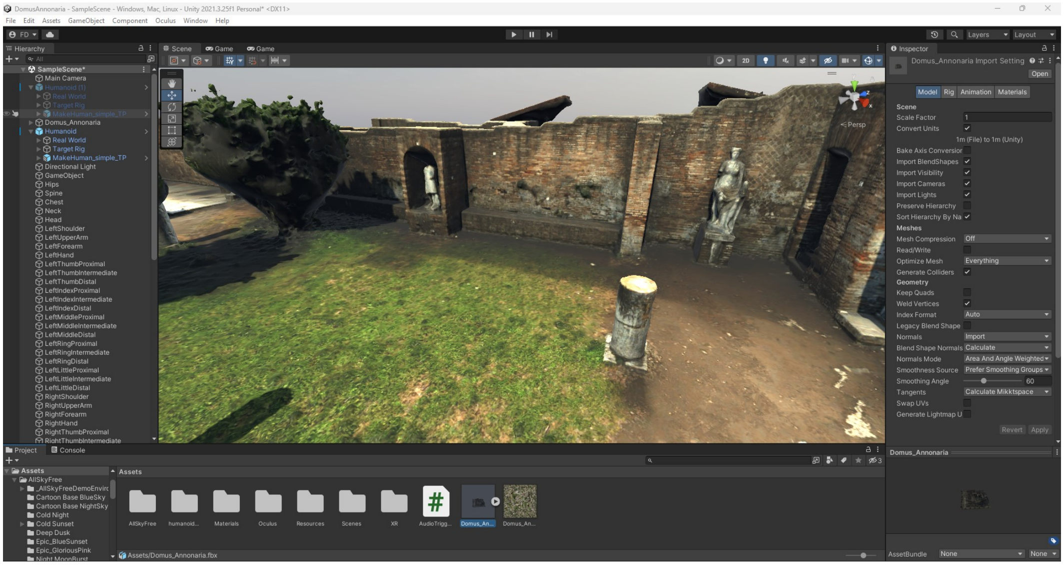


Figure 4.14: Interface of the Unity platform

The core of this implementation relies on the high-fidelity data obtained from the optimization of on-site surveys described in previous chapters. The survey campaign, conducted through high-performance NDTs such as Laser Scanners and UAV-based photogrammetry, resulted in the generation of massive datasets processed in Agisoft Metashape. It is important to establish how this type of data is to be distinguished from conventional BIM deliverables. While these have traditionally focused on parametric accuracy and semantic detail, utilizing idealized geometries to model structural elements in cases where this is important, this submission is concerned with the retention of photorealism. The photogrammetric processing deliver high-density meshes retaining not only the detailed geometric relationships from the resulting point cloud, but even more importantly, the high-resolution textures from the detailed photography. This integration allows for a distinct assessment of the asset's condition. As observed in preliminary applications (such as the survey of the Domus della Fortuna Annonaria), the photogrammetric approach yields exceptional results for static, rigid elements. Structural components like walls, columns, and statues utilize the high-resolution imagery to produce textures that are nearly indistinguishable from reality. However, a different behavior is observed regarding dynamic or complex natural elements, such as vegetation. Due to slight movements caused by wind during the image acquisition or laser scanning process, these elements often exhibit a lower level of geometric definition compared to the rigid built structures. By importing these textured models into Unity, it is possible to create an immersive Virtual Inspection Environment. This integration allows for a "Digital Inspection" of the asset, where the user can visually distinguish material degradation on static elements with high precision, while acknowledging the limitations in resolving non-static background elements (Figure 4.15).



Domus_Annonaria Import Setting

Model | Rig | Animation | Materials

Scene
Scale Factor: 1
Convert Units: ☑ 1m (File) to 1m (Unity)
Bake Axis Conversion: ☐
Import BlendShapes: ☑
Import Visibility: ☑
Import Cameras: ☑
Import Lights: ☑
Preserve Hierarchy: ☐
Sort Hierarchy By Name: ☑

Meshes
Mesh Compression: Off
Read/Write: ☐
Optimize Mesh: Everything
Generate Colliders: ☑

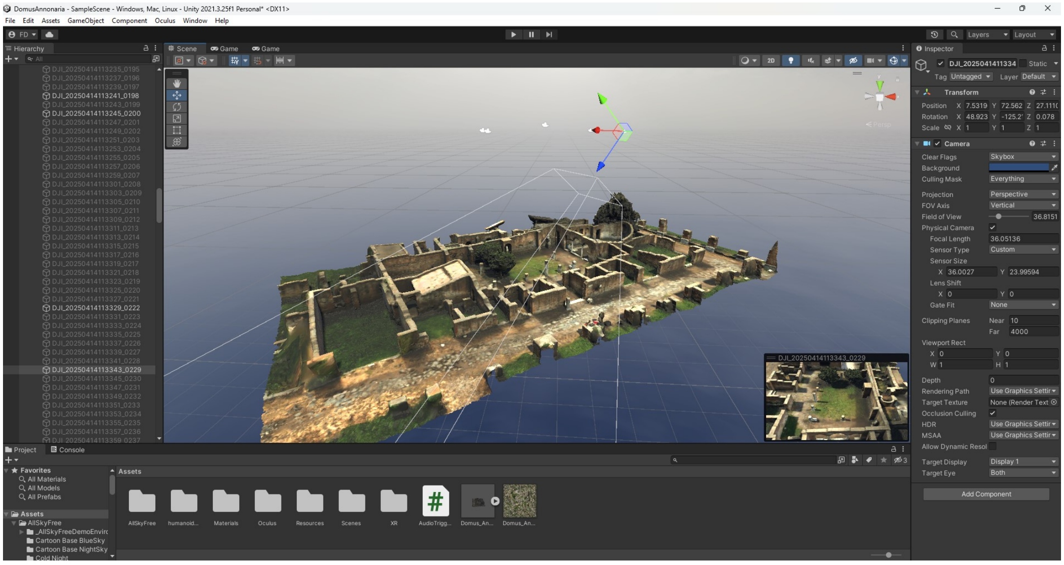
Geometry
Keep Quads: ☐
Weld Vertices: ☑
Index Format: Auto
Legacy Blend Shape Normals: ☐
Normals: Import
Blend Shape Normals: Calculate
Normals Mode: Area And Angle Weighted
Smoothness Source: Prefer Smoothing Groups
Smoothing Angle: 60
Tangents: Calculate Mikktspace
Swap UVs: ☐
Generate Lightmap UVs: ☐

Figure 4.15: Visual comparison within Unity

Beyond the geometric transfer, the utilization of the FBX (Filmbox) format facilitates a critical advancement in data traceability: the direct importation of the photogrammetric camera network. Unlike standard mesh exports, which often discard the acquisition parameters, this workflow preserves the extrinsic orientation parameters, specifically the spatial position (x, y, z) and rotational attitude (ω, ϕ, κ), of every single image captured during the survey.Within the Unity environment, this metadata is visualized as a cloud of frustums or view cones floating around the digital model. Each frustum represents the exact location and optical axis of the sensor at the moment of capture from UAV (Figure 4.16).

By importing the textured OBJ model into Unity, the platform is transformed from a passive viewer into an active virtual inspection environment. This integration facilitates a rigorous "Digital Inspection" workflow that is not limited to a specific case study but is methodologically applicable to any generic 3D structure and infrastructure model. The transition to the virtual world entails unique benefits over traditional on-site methods:

- Safety and accessibility: operators have the ability to move around to a total



☑ DJI_2025041411334 ☐ Static
Tag Untagged Layer Default
Transform
Position X 7.5319 Y 72.562 Z 27.111(
Rotation X 48.923 Y -125.2' Z 0.078
Scale X 1 Y 1 Z 1
☑ Camera
Clear Flags Skybox
Background
Culling Mask Everything
Projection Perspective
FOV Axis Vertical
Field of View 36.8151
Physical Camera ☑
Focal Length 36.05136
Sensor Type Custom
Sensor Size X 36.0027 Y 23.99594
Lens Shift X 0 Y 0
Gate Fit None
Clipping Planes Near 10 Far 4000
Viewport Rect X 0 Y 0 W 1 H 1
Depth 0
Rendering Path Use Graphics Settir
Target Texture None (Render Text
Occlusion Culling ☑
HDR Use Graphics Settir
MSAA Use Graphics Settir
Allow Dynamic Resol ☐
Target Display Display 1
Target Eye Both

Figure 4.16: Unity scene showing the camera positions

360-degree view of the structure. This feature allows them to analyze complex parts such as those underneath, bearings, and high piers, which have been scanned either using drones and/or laser scanning. This eliminates safety risks associated with elevated work, confined spaces, and busy roads.

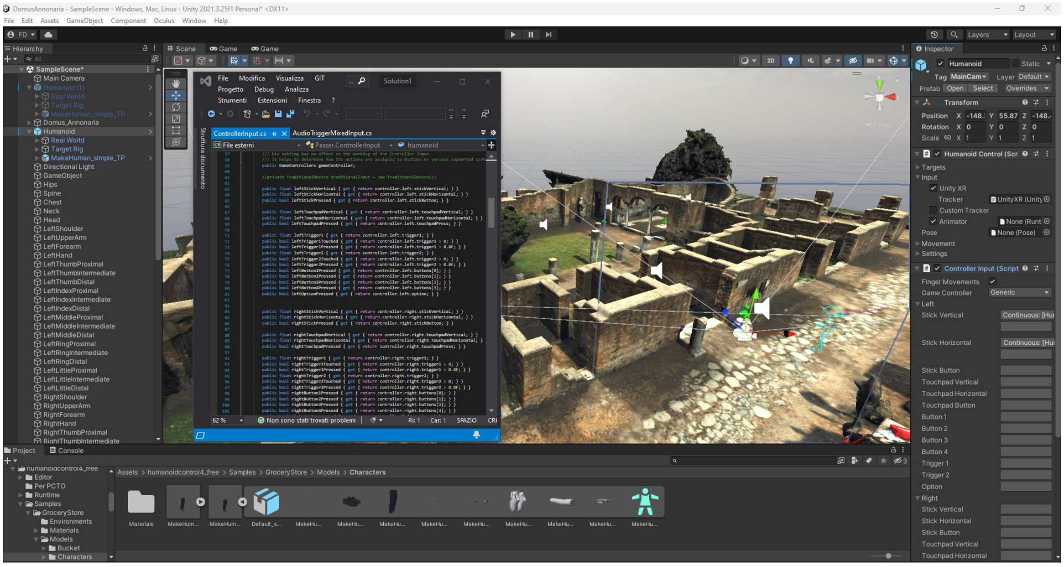
- Visual fidelity: the high-resolution texture mapping provides a level of realism to support accurate degradation identification (crack patterns, spalling, and moisture staining) beyond the capability offered by standard, untextured BIM objects.

To fully exploit the potential of this high-fidelity environment, the research workflow incorporates the Unity XR (Extended Reality) framework. This technology acts as the middleware allowing the real-time engine to communicate directly with external hardware, specifically Head-Mounted Displays (HMDs). The integration of HMDs shifts the user experience from a desktop-based observation to a fully immersive presence. Navigation within this virtual scene is managed through a dual-input system, programmable via C# scripting:

- Room-Scale locomotion: allowing the operator to physically walk within a defined real-world space to inspect details up close;

- Continuous movement: utilizing standard input peripherals (joysticks, controllers, or keyboards) to traverse large distances within the virtual model instantly.

The activation of this immersive mode is governed by specific backend logic. As illustrated in the following Figure 4.17, a script was used to initialize the XR subsystems, manage the stereoscopic rendering, and interpret the input data from the HMD controllers.



```
/// his setting has no effect on the working of the Controller Input.
/// It helps to determine how the actions are assigned to buttons or various supported cont
public GameControllers gameController;

//private TraditionalDevice traditionalInput = new TraditionalDevice();

public float leftStickVertical { get { return controller.left.stickVertical; } }
public float leftStickHorizontal { get { return controller.left.stickHorizontal; } }
public bool leftStickPressed { get { return controller.left.stickButton; } }

public float leftTouchpadVertical { get { return controller.left.touchpadVertical; } }
public float leftTouchpadHorizontal { get { return controller.left.touchpadHorizontal; } }
public bool leftTouchpadPressed { get { return controller.left.touchpadPress; } }

public float leftTrigger1 { get { return controller.left.trigger1; } }
public bool leftTrigger1Touched { get { return controller.left.trigger1 > 0; } }
public bool leftTrigger1Pressed { get { return controller.left.trigger1 > 0.8F; } }
public float leftTrigger2 { get { return controller.left.trigger2; } }
public bool leftTrigger2Touched { get { return controller.left.trigger2 > 0; } }
public bool leftTrigger2Pressed { get { return controller.left.trigger2 > 0.8F; } }
public bool leftButton1Pressed { get { return controller.left.buttons[0]; } }
public bool leftButton2Pressed { get { return controller.left.buttons[1]; } }
public bool leftButton3Pressed { get { return controller.left.buttons[2]; } }
public bool leftButton4Pressed { get { return controller.left.buttons[3]; } }
public bool leftOptionPressed { get { return controller.left.option; } }


public float rightStickVertical { get { return controller.right.stickVertical; } }
public float rightStickHorizontal { get { return controller.right.stickHorizontal; } }
public bool rightStickPressed { get { return controller.right.stickButton; } }

public float rightTouchpadVertical { get { return controller.right.touchpadVertical; } }
public float rightTouchpadHorizontal { get { return controller.right.touchpadHorizontal; } }
public bool rightTouchpadPressed { get { return controller.right.touchpadPress; } }

public float rightTrigger1 { get { return controller.right.trigger1; } }
public bool rightTrigger1Touched { get { return controller.right.trigger1 > 0; } }
public bool rightTrigger1Pressed { get { return controller.right.trigger1 > 0.8F; } }
public float rightTrigger2 { get { return controller.right.trigger2; } }
public bool rightTrigger2Touched { get { return controller.right.trigger2 > 0; } }
public bool rightTrigger2Pressed { get { return controller.right.trigger2 > 0.8F; } }
public bool rightButton1Pressed { get { return controller.right.buttons[0]; } }
public bool rightButton2Pressed { get { return controller.right.buttons[1]; } }
public bool rightButton3Pressed { get { return controller.right.buttons[2]; } }
public bool rightButton4Pressed { get { return controller.right.buttons[3]; } }
```

Figure 4.17: Unity XR - script for control humanoid

A significant advancement proposed in this methodology is the creation of a hybrid digital environment. Unity's open architecture allows for the simultaneous visualization of the as-is condition (the photogrammetric OBJ model) and the as-designed or as-built parametric model (BIM/IFC). When viewed through the immersive XR interface, this superposition enables a dual-layer analysis: the user can visually inspect the actual state of the infrastructure via the textured mesh while cross-referencing it with the theoretical geometric and semantic data contained in the BIM model. This capability facilitates immediate deviation analysis and clash detection between the real existing conditions, all performed within a safe, controlled virtual space.
Furthermore, leveraging Unity's inherent programmability via C# scripting, the platform was customized to evolve from a mere viewer into an active diagnostic tool. Custom scripts were developed to implement specific engineering functionalities:

- Virtual measurement tools: users can perform distance and area measurements directly on the 3D mesh within the virtual environment, verifying dimensions that might be difficult to measure on-site.

- Semantic annotation: the system allows inspectors to place digital tags or annotations directly onto the damaged portions of the mesh.

- Data circularity: crucially, these annotations are not static. The developed workflow allows for the data generated during the virtual inspection (e.g., inspector comments, defect classifications, coordinates) to be saved and exported as raw text data (.txt or .csv). This data can subsequently be re-imported into the BIM authoring software, populating the parametric objects with the new inspection data.

This loop capability demonstrates the infinite potential of the Unity platform: it acts not just as a visualization endpoint, but as an intermediate tool for optimization, allowing for a safe, preliminary virtual inspection that streamlines the subsequent on-site activities and enriches the final Digital Twin with verified diagnostic data.

To conclude, the methodological framework presented in this chapter demonstrates that the creation of a Digital Twin is not a static task but a dynamic, multi-stage process. The workflow begins with the automated generation of parametric geometry based on survey data, proceeds through rigorous semantic enrichment where defects are volumetrically mapped, and ensures data longevity via standardized IFC interoperability. Finally, the integration into the Unity environment transforms the model from a passive database into an interactive diagnostic tool.
This complete logical flow, bridging the gap between standard BIM authoring and advanced virtual inspection, is schematically summarized in Figure 4.18.

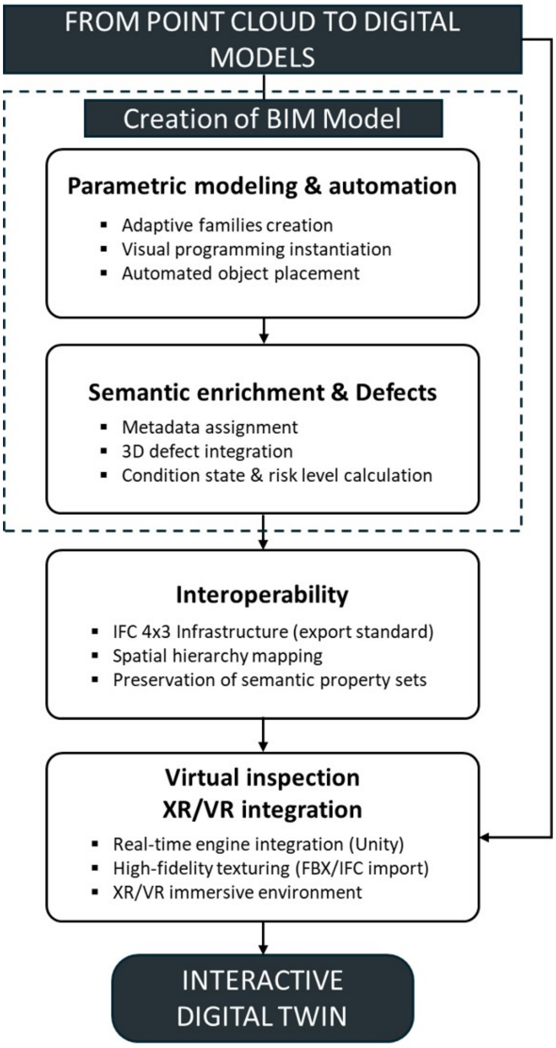


Figure 4.18: Workflow of the Scan-to-BIM and virtualization process: from parametric modeling to interactive Digital Twin.

Chapter 5

Case Studies

With the theoretical framework and the set of technology-related protocols established in the preceding chapters, it is crucial to move on to the practical assessment of the proposed approach through its application in real-life infrastructure systems. Transitioning from theoretical backgrounds to actual practices is vital not only for demonstrating the technical viability of the process but, more specifically, its applicability. Although the selection of the case studies presented in this thesis was not based on the intention of simply carrying out the same process on similar systems, it was rather intended to observe the particular context in which these highly specialized methods yield the highest value for specific engineering goals. As such, the research focuses on these two infrastructures that, despite the need to be closely monitored, have quite different morphological characteristics. This heterogeneity is intentional. It serves to demonstrate that the integrated use of high-performance Non-Destructive Technologies (NDT), specifically Terrestrial Laser Scanning (TLS) and UAV-based photogrammetry, is not a rigid, one size fits all solution, but a flexible framework capable of adapting to specific project targets. In both cases, the foundational step remains the optimization of the multi-sensor survey to generate a high-fidelity digital replica; however, the downstream application of this data diverges significantly to address the unique challenges posed by each site.

In both operational scenarios, the primary foundation is identical: the drastic reduction of on-site survey time and the enhancement of safety through the synergistic use of TLS and aerial photogrammetry. However, the subsequent utilization of this high-fidelity data diverges to explore two distinct horizons of the Digital Twin paradigm. In the case of Ponte Sisto, the research objective extends beyond mere geometric reconstruction. Here, the focus is placed on the visualization and interaction capabilities of the digital asset. The ultimate goal is to transpose the high-resolution survey into a Virtual Reality (VR) environment. This workflow demonstrates the potential for engineers to immersively navigate the inspection site at any time using head-mounted displays (HMDs), conducting detailed visual assessments in total safety. Furthermore, this approach sets the stage for 4D monitoring: by establishing a baseline digital model, future survey campaigns can be visually overlaid to perform immediate comparison and change detection, thereby fully digitizing the historical tracking of the infrastructure's health. Conversely, the Cave Bridge case study is oriented towards the structural and management rigor required by the Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Bridges. While the optimization of inspection times remains a key benefit, especially given the bridge's complex accessibility, the ultimate aim here is the creation of a structured Digital Data Repository. In this scenario, the transition from the point cloud to a parametric BIM model serves as the backbone for a comprehensive digital platform. This platform is designed not just for visualization, but to act as a central aggregator for defect recognition, anomaly mapping, and the calculation of monitoring parameters mandated by current regulations. The Cave Bridge application therefore demonstrates how the digitized model becomes the active interface for lifecycle management, hosting historical inspection data and enabling the seamless integration of future diagnostic results.

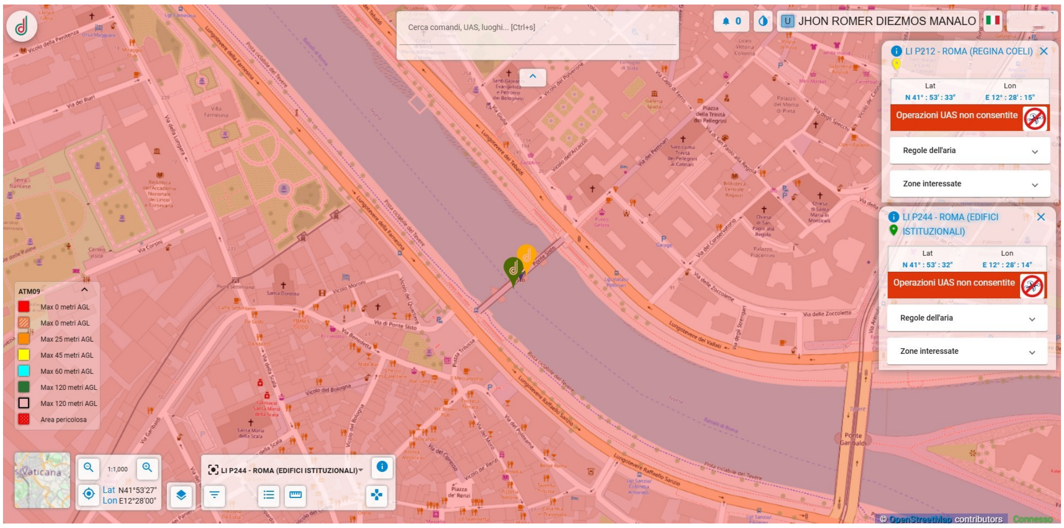
Through these two parallel yet distinct applications, this chapter highlights the transversal value of the proposed methodology: it is a unified workflow that creates a versatile digital base, capable of supporting both advanced virtual experiences and rigorous, standards-compliant asset management systems.

5.1 Ponte Sisto

Ponte Sisto was identified as the optimal case study to assess the specific segment of the workflow dedicated to Virtual Reality integration and immersive inspection. The selection of this specific infrastructure was dictated by the research necessity to test the limits of the proposed acquisition and modeling protocols within a dense, stratified urban context. The choice to apply the workflow to Ponte Sisto is motivated by the opportunity to intervene on a structure that presents a paradigmatic combination of structural, environmental, and logistical challenges. Unlike modern viaducts located in open fields, this Renaissance-era masonry arch bridge is embedded in a highly complex urban fabric, characterized by significant historical constraints, intensive daily pedestrian traffic, and a direct, dynamic interaction with the Tiber River hydraulic system (Figure 5.1). These specific boundary conditions were deemed essential to verify the applicability of immersive BIM framework. The aim was to demonstrate that high-performance Non-Destructive Technologies (specifically TLS and UAVs) could effectively generate a Digital Twin even where traditional access is hindered by the river and where the architectural complexity requires a level of visual fidelity that standard parametric modeling cannot achieve. Therefore, Ponte Sisto serves as the testing ground for the downstream application of the data. While the acquisition phase presented its own set of challenges, requiring coordination with multiple authorities for drone operations in restricted airspace, the primary engineering goal for this case study is to prove the value of transforming raw survey data into a navigable, immersive environment for safe, remote structural assessment.

Figure 5.1: Ponte Sisto

The bridge's location in the historic center of Rome, its proximity to architecturally prestigious buildings, and the presence of a wide surrounding area subject to strict constraints, including the Regina Coeli prison complex, necessitated a complex preliminary phase of programming and coordination. This involved extensive dialogue with competent authorities, primarily the Department for Infrastructure Development and Urban Maintenance (SIMU) of Roma Capitale. Specifically, obtaining authorizations for field survey activities required the involvement of multiple entities, particularly regarding the deployment of UAVs equipped with various payloads (optical, thermal camera and LiDAR sensors) in an airspace characterized by high regulatory, logistical, and environmental complexity. The site location required preventive work to obtain flight permits for prohibited areas such as LI-P212 (Regina Coeli) and LI-P244 (institutional buildings) (Figure 5.2), involving the Ministry of Justice and the Prefecture of Rome. The authorization process included the compilation of the Specific Operations Risk Assessment (SORA) and the securing of permits for public land occupation from the Local Police. This bureaucratic and authorization phase proved to be a fundamental component of the research, confirming the feasibility of accessing total infrastructure coverage even in highly restricted urban zones.



LI P212 - ROMA (REGINA COELI)

Lat	Lon
N 41° : 53' : 33"	E 12° : 28' : 15"

Operazioni UAS non consentite

LI P244 - ROMA (EDIFICI ISTITUZIONALI)

Lat	Lon
N 41° : 53' : 32"	E 12° : 28' : 14"

Operazioni UAS non consentite

Figure 5.2: D-flight site - LI-P212 and LI-P244

5.1.1 Data acquisition and processing

A preliminary morphological and logistical analysis of the spaces adjacent to the infrastructure was conducted to verify accessibility. It was determined that all structural components were adequately detectable, allowing for the optimal use of high-resolution Non-Destructive Testing (NDT) technologies, especially for use TLS. Following authorization, the survey proceeded using high-performance instrumentation. Given the operational configuration of the static laser scanner, four scan stations were strategically positioned in the lower section of the bridge along the Tiber embankments, two on each bank, to guarantee complete acquisition of the structural elements while minimizing the impact on pedestrian traffic (Figure 5.3 and 5.4); . This setup allowed for the coverage of nearly the entire extent of the work; any shadow zones due to the bridge's geometry were subsequently compensated for by UAV-based acquisitions.

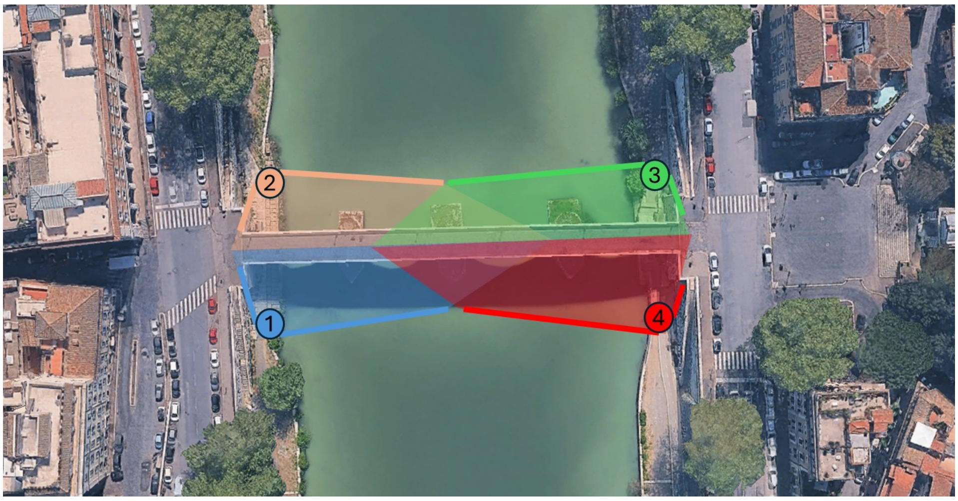


Figure 5.3: Positions of Terrestrial Laser Scanner

Figure 5.4: Position n.2 of Laser Scanner

After the ground survey, a comprehensive aerial survey was conducted to capture information related to the higher structure and to compensate for the gaps associated with terrestrial scanning. This stage of the study adopted a multi-platform approach to ensure a diverse dataset is generated. The simultaneous operation of the UAVs ensured a thorough analysis of the infrastructure and proved the concept of operating a variety of payloads. The DJI Mavic 4T was deployed specifically for thermographic surveying. The integration of thermal imagery provided a critical diagnostic layer, enabling the detection of surface temperature variations that are often indicative of underlying pathologies. The DJI Matrice 350 RTK was employed as the primary platform for both geometric and textural reconstructions (Figure 5.5).

Figure 5.5: Dji Matrice 350 with L2 Payload and DJI Mavic 4T

The DJI Matrice 350 RTK was equipped with different payloads according to the specific requirement for acquiring data:

- Zenmuse P1: this full-frame sensor was used in the mission to provide high-resolution photogrammetry. In abidance with the urban-flight safety guidelines and the rules for the protection of the historic property, the aircraft maintained a standoff distance of around 20 meters from the bridge surface. Despite maintaining the safety distance, the high-resolution image provided a GSD of around millimeters. The flight mission was complex, involving the capture of over 1,000 images taken at varying altitudes and oblique angles. This multi-tiered strategy was essential to fully resolve the intricate geometry of the spans and to capture the bridge intrados with adequate overlap.
- Zenmuse L2: complementing the photogrammetry, the L2 LiDAR sensor facilitated direct 3D point cloud generation, penetrating vegetation foliage on the riverbanks and providing an immediate geometric reference for the photogrammetric scaling.

To ensure the metric reliability of the model, the aerial and terrestrial datasets were anchored to a rigorous global reference system. The geolocalization process was not limited to standard GNSS positioning; rather, it employed a hybrid approach combining GNSS receivers with high-precision measurements and a Total Station. This dual-instrumentation strategy ensured the precise alignment and translation of the entire digital model. By integrating data from Laser Scanners, UAVs, GNSS, and Total Stations, the workflow achieved a robust data fusion. As detailed in the methodological framework of this thesis, this convergence of multi-source data facilitates reliable cross-analyses, ensuring that the final model is not merely a visual representation, but a metrically accurate tool capable of monitoring potential structural deformations over time.

Data acquired from the four TLS stations were imported into the proprietary software for initial processing. The registration was verified through the aforementioned control network (Total Station and GNSS), resulting in a final alignment error of less than one millimeter, a value compliant with high-precision 3D documentation standards. A specific challenge in processing the Ponte Sisto dataset was the management of noise caused by the river environment. The water surface, by absorbing or deflecting laser signals, generated spurious points near the base of the piers (Figure 5.6). Furthermore, the scanner inevitably captured non-relevant surrounding elements, such as vegetation and adjacent buildings. Consequently, a targeted cropping and filtering operation was performed immediately upon import to isolate the relevant structural volume (piers, abutments, intrados, and deck). Density and statistical outlier filters were subsequently applied to remove isolated anomalies, resulting in a consolidated, high-density point cloud ready for modeling.

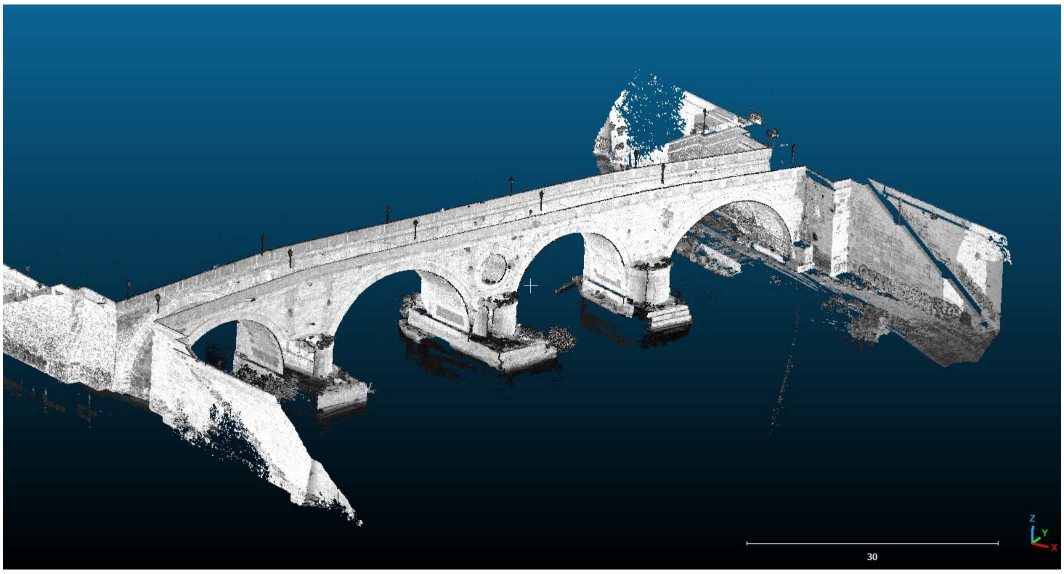


Figure 5.6: Result from Terrestrial Laser Scanner

Regarding the aerial component, the LiDAR point cloud acquired by the Zenmuse L2 sensor was processed and exported via DJI Terra, while the photogrammetric dataset from the Zenmuse P1 was processed in Agisoft Metashape. The latter was crucial for generating a textured mesh with high chromatic fidelity (Figure 5.7). The final integration of these datasets provided a comprehensive digital replica of the bridge, successfully merging the geometric precision of the TLS (for the intrados and lower piers) with the textural richness and coverage of the photogrammetry (for the elevations and upper deck).

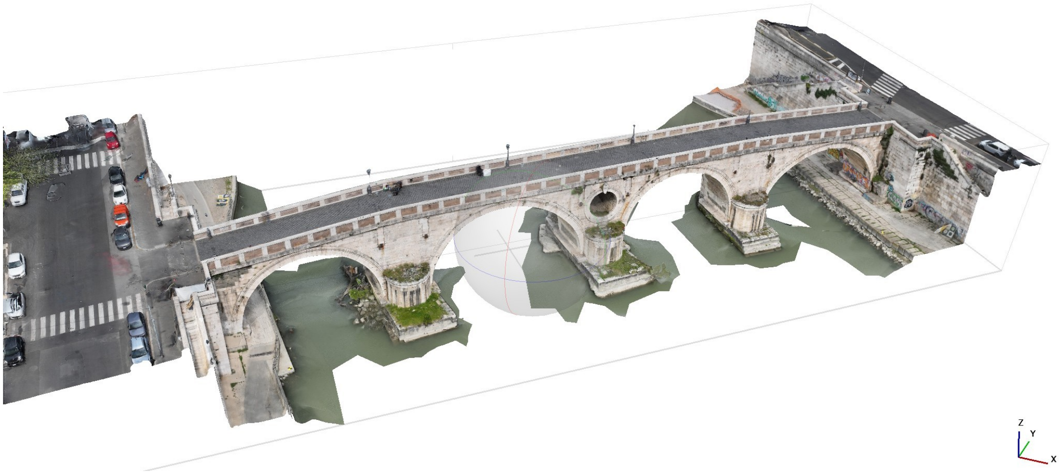


Figure 5.7: Result from photogrammetry

5.1.2 From Scan-to-BIM to Virtual Reality

Having final point cloud consolidation, the process moved on to Scan-to-BIM. Scan-to-BIM is an important process in converting unstructured geometric data points into a structured database that is object-oriented. The modeling process was conducted within Autodesk Revit, utilizing the segmented point cloud as a direct geometric reference. As has been shown in methodological chapters, the initial segmentation of the point cloud was an important step in optimizing this approach. The separation of isolated clusters of points corresponding to particular structural elements (for example, piles, arches, spandrel walls, and deck surfaces) allowed for automating the boundaries of formats for modeling. However, given the historical nature of Ponte Sisto and its irregularities, typical of masonry heritage, standard parametric libraries were insufficient (Figure 5.8). Consequently, the modeling required the creation of custom adaptive families. This approach allowed for the generation of a high Level of Detail (LOD) model that faithfully adheres to the morphological captured by the laser scanner, avoiding the over-simplification often found in traditional design-intent modeling (Figure 5.9).

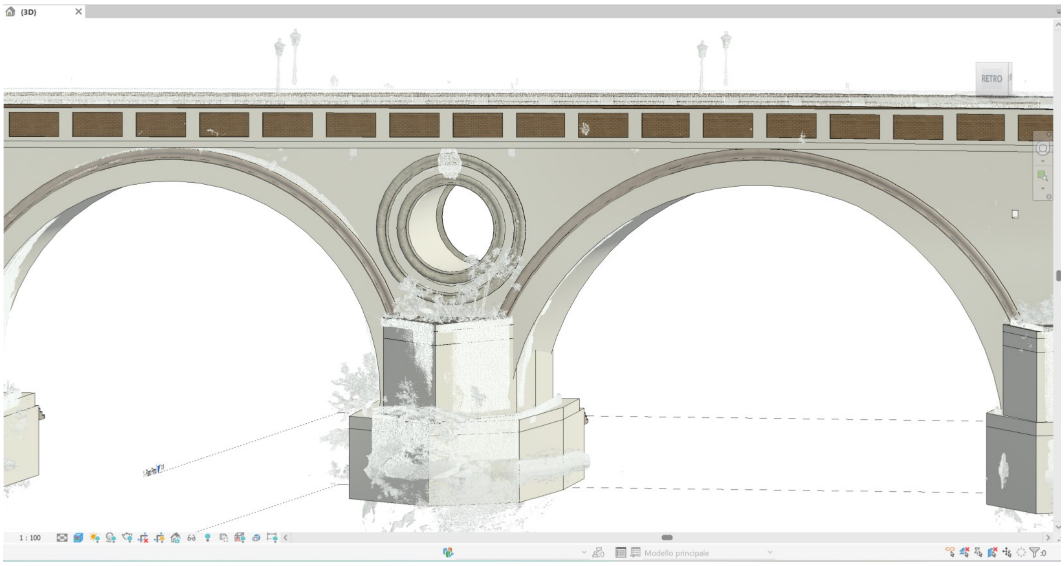


Figure 5.8: Revit model with overlapping point cloud

This BIM delivers a dual role: firstly, it provides a geometric digital model useful for structural analysis. Secondly, and more significantly to this project, it provides a semantic repository. For each modeled object, such as a specific brick arch or a stone parapet, information from the diagnosis process was appended to create a browsable database where geometric information was inextricably linked with information related to maintenance.

The final and most innovative step of the workflow involved transcending

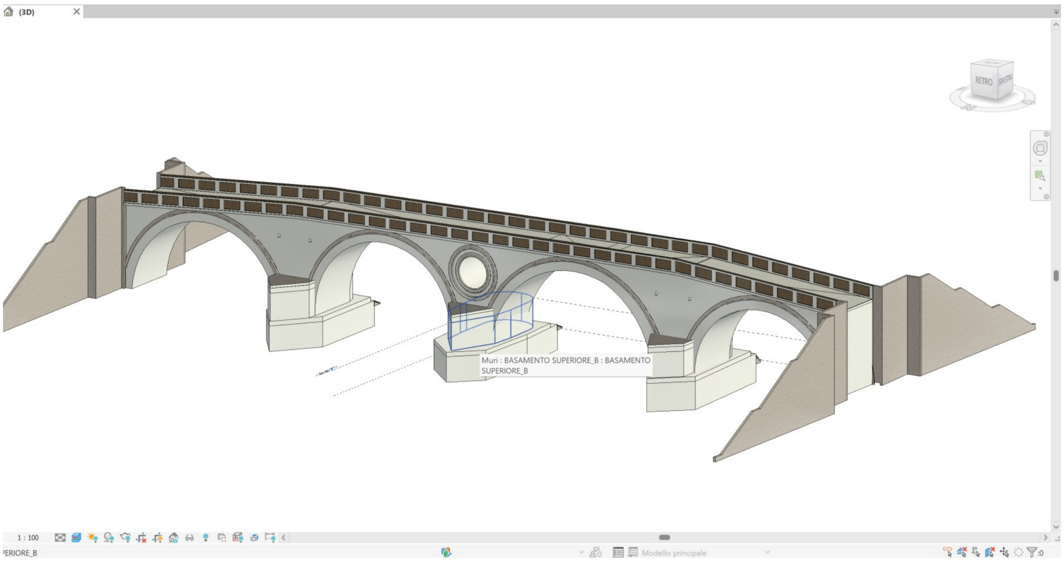


Figure 5.9: Result of Revit model

traditional desktop-based visualization by importing the digital assets into a real-time interactive environment. Both the high-fidelity textured FBX model (derived from the photogrammetric process in Metashape) and the parametric BIM/IFC model (exported from Revit) were imported into the Unity. As illustrated in Figure 5.10, the operational interface of the software is organized to facilitate the management of these complex datasets. The figure depicts the standard Unity layout, where the Project Browser located at the bottom of the screen organizes the directory of project folders and raw assets, while the Hierarchy panel on the left lists the specific digital models instantiated within the scene, confirming the successful importation and structured layering of both the photogrammetric mesh and the BIM objects.


Ponte Sixto - SampleScene - Windows, Mac, Linux - Unity 2021.3.25f1 Personal* <DX11>

Scene
Scale Factor 1
Convert Units ☑
1cm (File) to 1m (Unity)
Bake Axis Conversior ☐
Import BlendShapes ☑
Import Visibility ☑
Import Cameras ☑
Import Lights ☑
Preserve Hierarchy ☐
Sort Hierarchy By Na ☑
Meshes
Mesh Compression Off
Read/Write ☐
Optimize Mesh Everything
Generate Colliders ☑
Geometry
Keep Quads ☐
Weld Vertices ☑
Index Format Auto
Legacy Blend Shape ☐
Normals Import
Blend Shape Normals Calculate
Normals Mode Area And
Smoothness Source Prefer Sm
Smoothing Angle 60
Tangents Calculate
Swap UVs ☐
Generate Lightmap U ☐

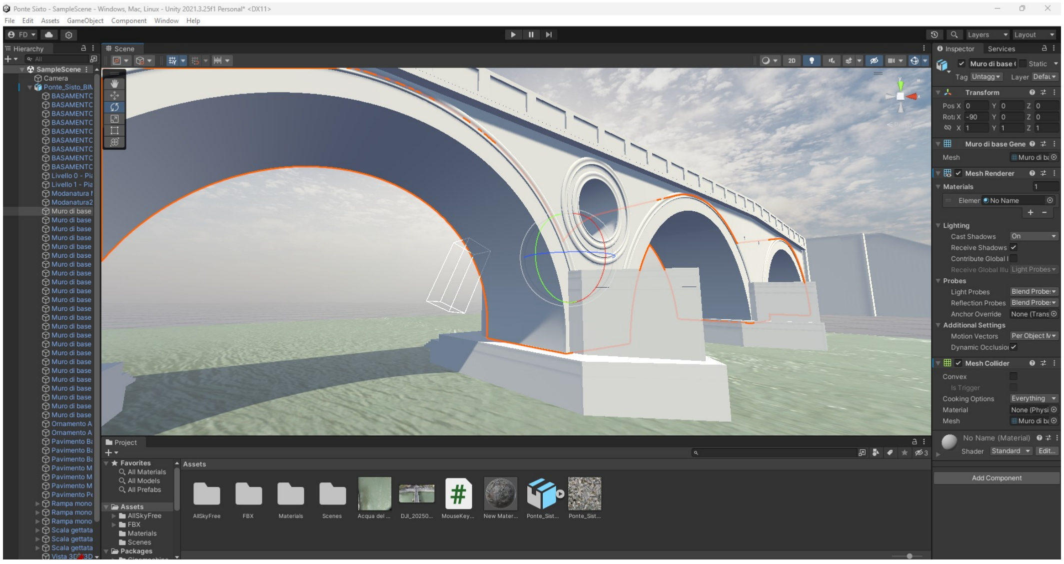
Pos X 0 Y 0 Z 0
Rot X 0 Y 0 Z 0
X 1 Y 1 Z 1

Assets/Ponte_Sisto_Photogrammetry_model.obj

Figure 5.10: Import different models in Unity

A fundamental prerequisite for this integration was the strict maintenance of the shared coordinate system. Since both models share the same georeferencing established during the GNSS survey, they could be perfectly superimposed within the Unity scene without manual adjustment. This alignment enables a dual-visualization mode: the user can toggle between the as-is photorealistic mesh (to inspect surface degradation) and the "Informative" BIM model (to access structural data), or view them simultaneously to detect deviations.

As shown in the Figure 5.11, the resulting visualization of the isolated BIM layer clearly shows that the application of the Autodesk Revit software has led to the successful instantiation of the structural entities created there as part of the graphic engine environment. Crucially, the instantiated semantics of the real-time engine software reflect the object-oriented nature of the IFC standard, which identifies discrete objects such as piers, arches, and parapets, rather than the combined model. The ability to perform the aforementioned task allows the user to select and directly manipulate the objects to obtain new information or to input fresh data.



Muro di base (☐ Static
Tag Untagged Layer Default
Transform
Pos X 0 Y 0 Z 0
Rot X -90 Y 0 Z 0
X 1 Y 1 Z 1
Muro di base Gene
Mesh Muro di ba
☑ Mesh Renderer
Materials 1
Elemen No Name
Lighting
Cast Shadows On
Receive Shadows ☑
Contribute Global I ☐
Receive Global Illu Light Probes
Probes
Light Probes Blend Probes
Reflection Probes Blend Probes
Anchor Override None (Trans
Additional Settings
Motion Vectors Per Object M
Dynamic Occlusion ☑
☑ Mesh Collider
Convex ☐
Is Trigger ☐
Cooking Options Everything
Material None (Physi
Mesh Muro di ba
No Name (Material)
Shader Standard Edit...

Figure 5.11: Import BIM/IFC Model in Unity

Leveraging the millimetric precision and the high-resolution textures obtained from the multi-camera UAV survey, the virtual environment achieves a near-photorealistic quality. Figure 5.12 highlights the level of detail achieved: the resolution is sufficient to permit the operator to virtually approach the surface to the point of contact, enabling the clear identification of minute material defects, such as mortar loss, cracking patterns, or moisture stains, with a clarity comparable to a physical on-site examination.

To fully exploit this potential, the system was integrated with a Head-Mounted

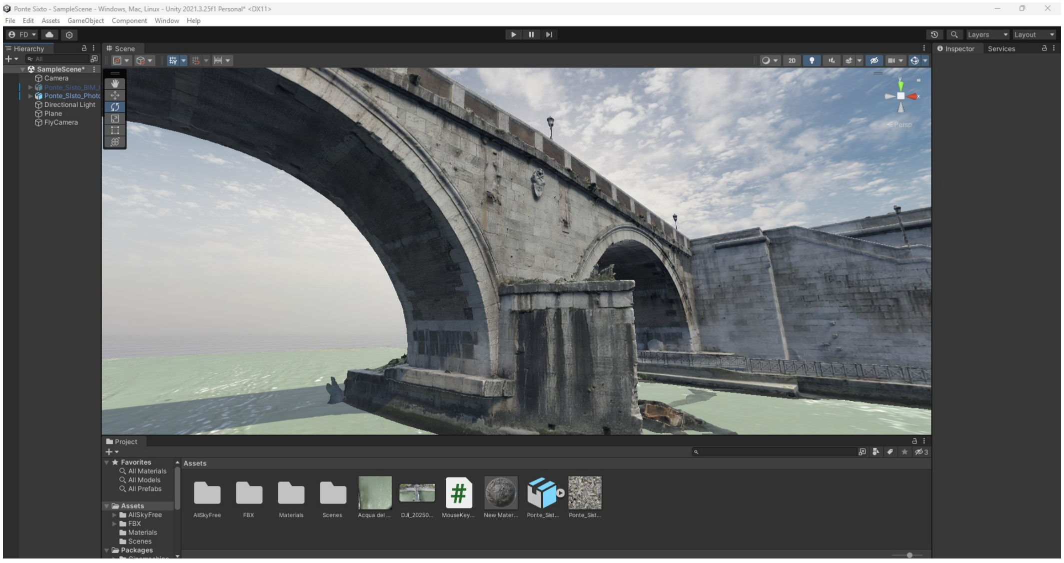
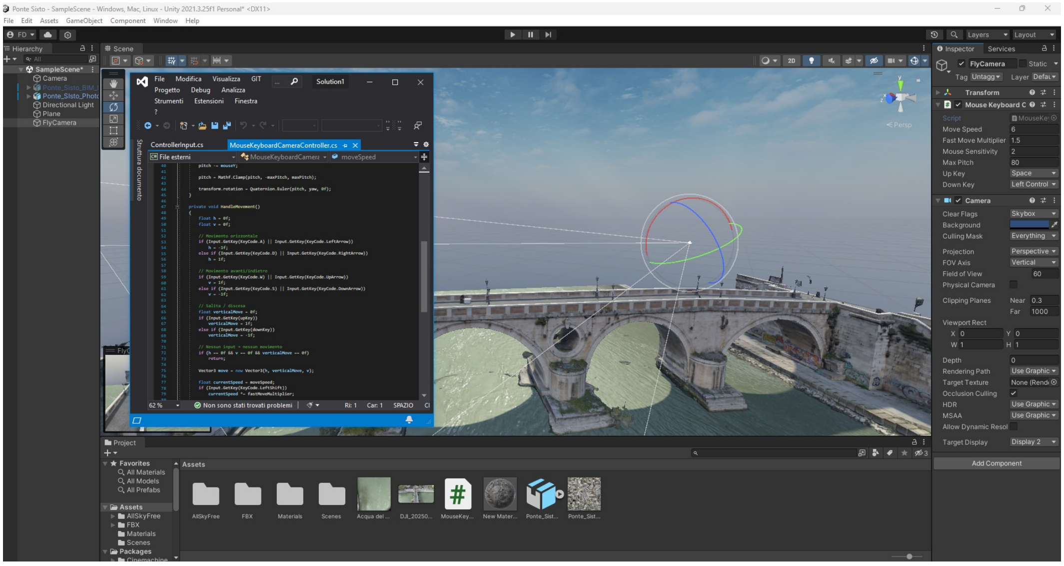


Figure 5.12: Detail view in Unity

Display (HMD) via the Unity XR framework. This hardware integration shifts the inspection paradigm from observation to immersion. To facilitate unrestricted movement, a custom C# navigation script was developed, as shown in Figure 5.13. Unlike standard gravity-bound terrestrial navigation, this script enables 6-Degrees-of-Freedom (6DoF) flight, allowing the operator to freely maneuver around the structure. This feature is particularly significant for inspecting the bridge's complex geometries, such as the intrados, under-arch masonry, and upper pier sections, areas that are physically inaccessible from the ground or typically require expensive bridging equipment to inspect on-site.



```
        pitch -= mouseY;

        pitch = Mathf.Clamp(pitch, -maxPitch, maxPitch);

        transform.rotation = Quaternion.Euler(pitch, yaw, 0f);
    }

    private void HandleMovement()
    {
        float h = 0f;
        float v = 0f;

        // Movimento orizzontale
        if (Input.GetKey(KeyCode.A) || Input.GetKey(KeyCode.LeftArrow))
            h = -1f;
        else if (Input.GetKey(KeyCode.D) || Input.GetKey(KeyCode.RightArrow))
            h = 1f;

        // Movimento avanti/indietro
        if (Input.GetKey(KeyCode.W) || Input.GetKey(KeyCode.UpArrow))
            v = 1f;
        else if (Input.GetKey(KeyCode.S) || Input.GetKey(KeyCode.DownArrow))
            v = -1f;

        // Salita / discesa
        float verticalMove = 0f;
        if (Input.GetKey(upKey))
            verticalMove = 1f;
        else if (Input.GetKey(downKey))
            verticalMove = -1f;

        // Nessun input → nessun movimento
        if (h == 0f && v == 0f && verticalMove == 0f)
            return;

        Vector3 move = new Vector3(h, verticalMove, v);

        float currentSpeed = moveSpeed;
        if (Input.GetKey(KeyCode.LeftShift))
            currentSpeed *= fastMoveMultiplier;
```

Non sono stati trovati problemi

FlyCamera
Tag Untagged Layer Default
Script MouseKeyboardCameraController
Move Speed 6
Fast Move Multiplier 1.5
Mouse Sensitivity 2
Max Pitch 80
Up Key Space
Down Key Left Control
Clear Flags Skybox
Culling Mask Everything
Projection Perspective
FOV Axis Vertical
Field of View 60
Physical Camera ☐
Clipping Planes Near 0.3 Far 1000
Viewport Rect X 0 Y 0 W 1 H 1
Depth 0
Rendering Path Use Graphic
Target Texture None (Rend
Occlusion Culling ☑
HDR Use Graphic
MSAA Use Graphic
Allow Dynamic Resol ☐
Target Display Display 2

Figure 5.13: Script code to navigate the model

Ultimately, this implementation establishes the workflow as a robust tool for safe, remote inspection. As depicted in Figure 5.12, the engineer can assess the state of conservation directly within the Digital Twin while remaining in a secure office environment. This decoupling of the inspection process from physical site constraints significantly reduces personnel exposure to risks associated with working at heights or near traffic, effectively overcoming the logistical limitations of the real-world site.

Figure 5.14: Operator with HMD

5.2 Ponte Cave

An examination of the second infrastructure chosen for the experimental phase is that of the Bridge of Cave, located in the Cave municipality inside the Rome metro environment. This infrastructure is characterized by a peripheral, semi-rural placement that is vastly different from the historical-urban concentrated environment that is experienced in the case of the Ponte Sisto bridge. In terms of its importance as far as its targeted community is concerned, the Bridge of Cave is placed in such a pivotal position as to be the leading, or in certain cases the sole, way that certain areas manage to reach the city center. Morphologically, the bridge spans a deep valley characterized by dense vegetation and uneven terrain (Figure 5.15). The structure faces significant accessibility constraints: while the abutments and the base of certain piers are approachable from the lower ground level, the significant vertical clearance, reaching a maximum height of approximately 27 meters from the ground level to the deck, renders traditional close-range visual inspection extremely hazardous and, in some areas, technically unfeasible without the use of specialized lifting equipment (e.g., by-bridge trucks). The selection of this specific viaduct was driven by the necessity to test the versatility of the multi-sensor acquisition protocol in a scenario dominated by natural obstacles rather than urban ones. The presence of a wooded area surrounding the piers and the significant height difference offered an ideal testbed for optimizing the synergy between TLS and UAV-based photogrammetry. Unlike the previous case study here the primary objective of the survey optimization was to overcome physical inaccessibility. The research focused on defining flight plans capable of penetrating the vegetation gaps to capture the lower structural elements while ensuring safe standoff distances at high altitudes for the deck inspection. This operational context serves to demonstrate the methodology's capability to provide complete geometric coverage even when the zero-level access is severely compromised.

Figure 5.15: Cave Bridge

While the survey phase shares the technical rigor of the previous application, the downstream objective for the Bridge of Cave shifts the focus from virtual inspection to data management and interoperability. The primary goal of this case study is the generation of a comprehensive Building Information Model (BIM) designed to function as a centralized data repository. In this workflow, the BIM environment is not merely used for 3D representation but is structured to act as the *single source of truth* for the asset.

The experimental activity aims to demonstrate how the high-fidelity data collected on-site can be encapsulated within the parametric model and exported in open standard formats (IFC), ensuring that no information is lost during the data exchange process between different stakeholders. This approach addresses the critical industry need for preserving data integrity throughout the asset's lifecycle. Furthermore, to assess its scalability, this specific case study has been integrated into broader research initiatives, specifically the MLazio project and the PIASTRE research program. Within these frameworks, the digitized model of the Bridge of Cave was successfully implemented into a digital platform, serving as the foundational node for the development of an optimized Bridge Management System (BMS), capable of hosting historical data, inspection logs, and monitoring parameters in a unified digital ecosystem.

5.2.1 Data acquisition and processing

Due to its major positioning in a heavily forested region, the first stage of the scanning exercise required certain logistical considerations to ensure detectability of the infrastructure features. Also identified within the site analysis, the heavily forested region around the piers and abutments posed a major risk of occlusion for ground and airborne sensors. Consequently, a formal request was submitted to the infrastructure managing entity to perform targeted vegetation clearance (pruning and mowing) in the immediate vicinity of the bridge. This preparatory step was strictly necessary to guarantee an optimal survey condition, maximizing the line-of-sight for the laser scanner and ensuring clear optical paths for the photogrammetric acquisition. Following the site clearance, the operational workflow proceeded with the materialization of the topographic network, adhering to the protocols established in the previous chapters. A series of high-reflectivity targets were strategically installed on the bridge structure to be measured via Total Station, creating a local rigid network. Simultaneously, additional targets were placed on the ground in open-sky areas to be surveyed using GNSS receivers. This dual approach ensured the precise global georeferencing of the entire dataset, linking the local structural geometry to the cartographic reference system.

The terrestrial data was acquired using a Polaris Teledyne Optech laser scanner. In consideration of the morphological limitations of the site, specifically the tight spacing between the piers and the dense vegetation cover, the scanning process was designed with a balance of coverage and efficiency in mind. Moving the heavy terrestrial scanner over the topographic relief posed operational challenges; thus, the scanning stations were limited to four stations, two on each side of the valley (Figure 5.16 and 5.17). This configuration was calculated to capture the essential geometry of the lower piers and the intrados without incurring the excessive time penalties associated with multiple station relocations. The resulting point clouds served as the geometric baseline for the lower sections of the bridge.

Following the ground operations, the survey advanced to the aerial acquisition

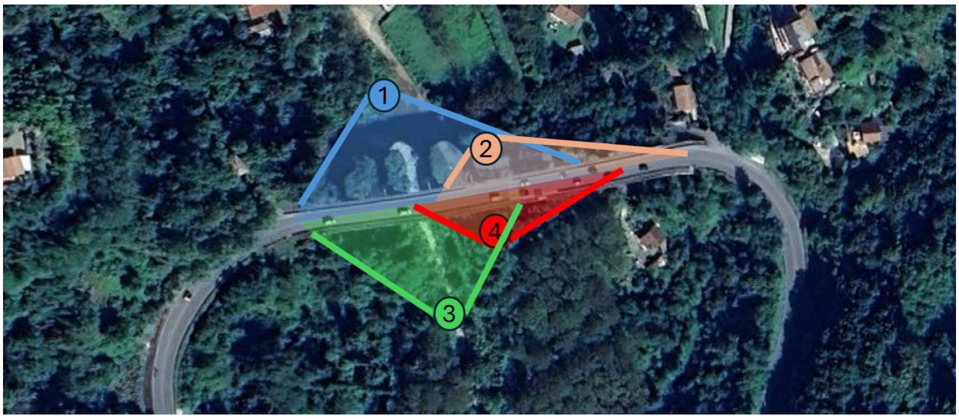
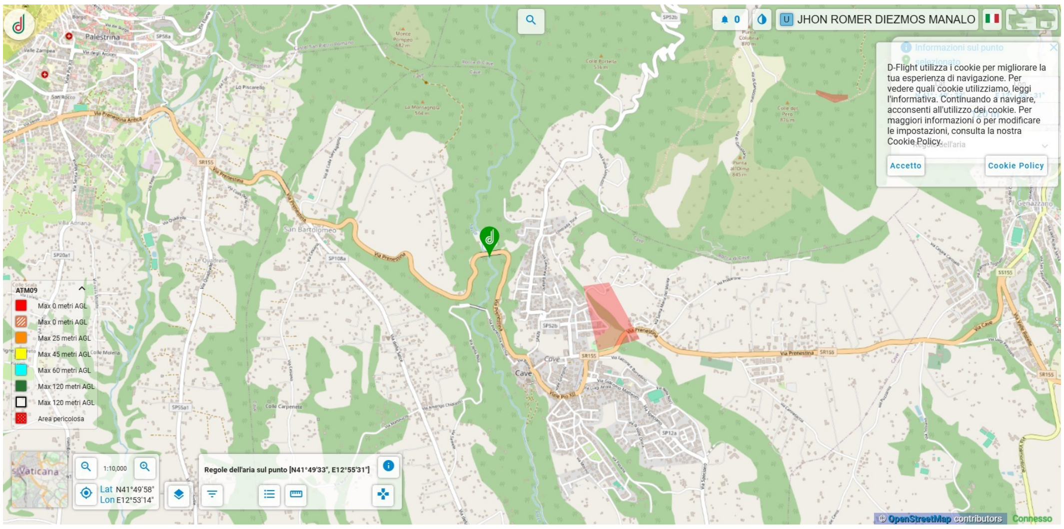


Figure 5.16: Positions of stations of Terrestrial Laser Scanner

Figure 5.17: Position n.1 of Laser Scanner

phase. The aerial platforms utilized the same set of instruments as the last case. The DJI Matrice 350RTK was utilized with interchangeable payload systems (Zenmuse P1 for RGB and Zenmuse L2 for LiDAR), and the DJI Mavic 4T was utilized for the thermal analysis. Unlike the urban constraints of the Ponte Sisto case study, the airspace over the Bridge of Cave presented fewer regulatory restrictions (Figure 5.18), allowing for the implementation of automated flight missions. The flight planning was executed using the DJI Pilot 2 software, leveraging the "Terrain Follow" and "Oblique" modes. The automation parameters were meticulously defined based on two critical inputs:

- Safety clearance: the highest point of the greatest obstacle, including vegetation and pylons, was determined to be the safety limit to avoid collisions.
- Resolution: the flight route was designed by the software automatically, depending on the target Ground Sampling Distance and the required overlap, thus ensuring an equal level of detail over the entire structure.



D-Flight utilizza i cookie per migliorare la tua esperienza di navigazione. Per vedere quali cookie utilizziamo, leggi l'informativa. Continuando a navigare, acconsenti all'utilizzo dei cookie. Per maggiori informazioni o per modificare le impostazioni, consulta la nostra Cookie Policy.

Regole dell'aria sul punto [N41°49'33", E12°55'31"]

Figure 5.18: D-flight site for Bridge of Cave

A critical aspect of the aerial survey involved the management of safety risks related to active traffic. Although the site is located in a semi-rural context, the bridge remains an active roadway. Current aviation regulations strictly prohibit the overflight of moving vehicles for safety reasons. Throughout the transverse phases of the flight, in which the unmanned aerial vehicle (UAV) had to move from one side of the bridge deck to the other, a safety procedure was agreed upon collaboratively with the research team. Real-time observation of the position of the UAV through the use of the remote control allowed the ground team to coordinate the temporary stops of traffic on the road. The traffic was paused in both directions for about 20 seconds. It has proved useful for identifying the operational feasibility of UAV operations on existing infrastructure. While traffic density on the secondary road chosen for this experiment made the stop and go method of operation viable without significantly impairing traffic flow, this highlights an important potential limitation of this approach for high traffic conditions, such as freeways or major roads, where these types of interruptions would prove impractical.

The raw data acquired from the TLS campaign was initially processed using the proprietary software of the laser scanner manufacturer (Atlascan). The primary registration of the four scan stations was constrained by the topographic network established via Total Station and GNSS, resulting in a consolidated point cloud exported in .las format. During the post-processing phase, specific filtration algorithms were applied, specifically DTM (Digital Terrain Model) filters to classify ground points and statistical outlier removal filters to mitigate noise. However, an analysis of the resulting dataset reveals the operational limitations dictated by the site's morphology. As illustrated in Figure 5.19, the terrestrial coverage is geometrically incomplete. Significant occlusions are observable on the upper sections of the piers and, most notably, on the right side of the valley corresponding to Scan Station No. 4, where dense vegetation and steep terrain prevented effective data capture. Consequently, it was determined that the TLS dataset alone was insufficient for the global geometric reconstruction of the bridge. Nevertheless, the data retains a high critical value: due to its superior radiometric quality and point density, the TLS cloud is utilized specifically for the mapping of surface anomalies along the accessible longitudinal sections. This application aligns with the methodology described in Section 4.2.2, where high-resolution terrestrial data serves as the diagnostic layer for material degradation analysis, which is subsequently mapped onto the BIM elements.

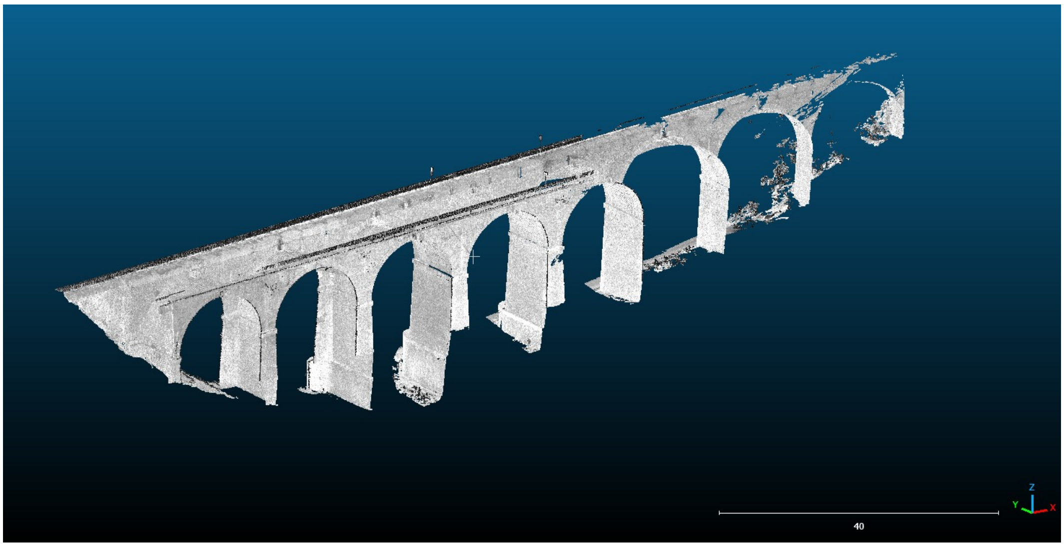


Figure 5.19: Visualization of the TLS point cloud coverage

To achieve complete geometric coverage, the workflow relied on the aerial datasets.

- Photogrammetry (Zenmuse P1): the automated flight mission resulted in the acquisition of over 3,500 images. These were processed in Agisoft Metashape, generating a dense point cloud with a ground resolution (GSD) of approximately 2-3 mm. As shown in Figure 5.19, the high redundancy of the shots ensured the reconstruction of a seamless model, filling the gaps left by the terrestrial scanner.
- LiDAR (Zenmuse L2): the aerial laser scanning data was processed via DJI Terra, providing a direct structural point cloud that penetrated the canopy cover, offering a geometric reference for the photogrammetric scale.

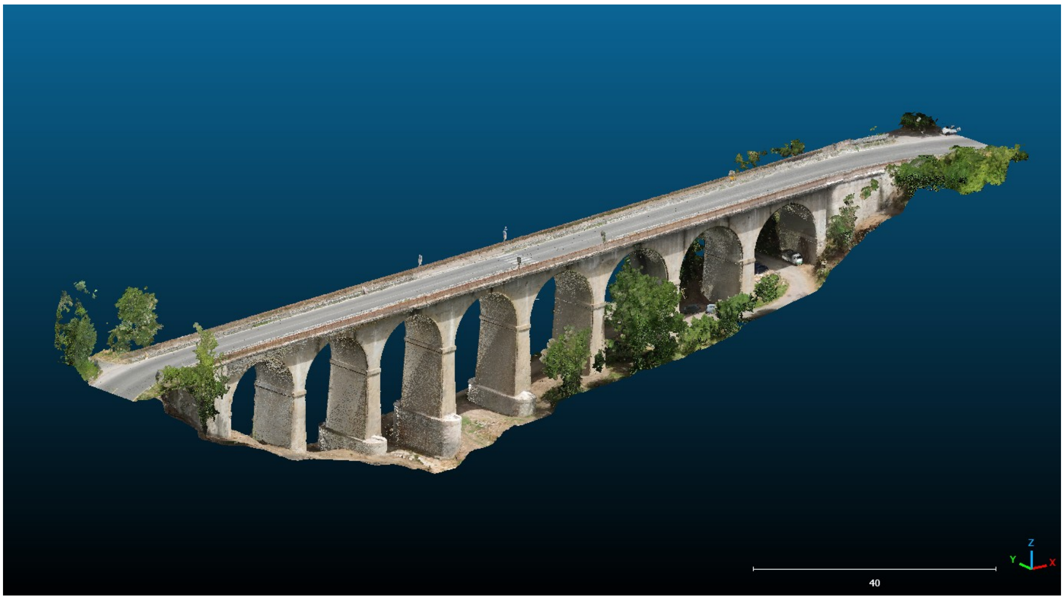


Figure 5.20: Point Clouds from Photogrammetry

The final step of the data preparation involved the fusion of the filtered terrestrial cloud with the aerial datasets to create a unified, multi-scale point cloud. This comprehensive dataset formed the basis for the segmentation process. Unlike the complex historical irregularities of Ponte Sisto, the Bridge of Cave features relatively standard geometries typical of masonry infrastructure. This morphological simplicity allowed for a higher degree of automation in the classification phase.

As the methodological framework presented in 3.3 has already extensively demonstrated the algorithms for extracting macro-structural elements, such as foundations, piers, and arches, this section will not reiterate those procedures. Instead, the focus here shifts to the road infrastructure components, a process not previously detailed. Specifically, this case study required the isolation of the superstructure elements, namely the road pavement, guardrails, and sidewalls, which are critical for defining the alignment in the subsequent infrastructure modeling phase. The extraction process employed a hierarchical filtering strategy based on geometric descriptors. Initially, a coarse filter based on the Height (Z) coordinate was applied to isolate the bridge deck level from the underlying valley and piers (Figure 5.21).

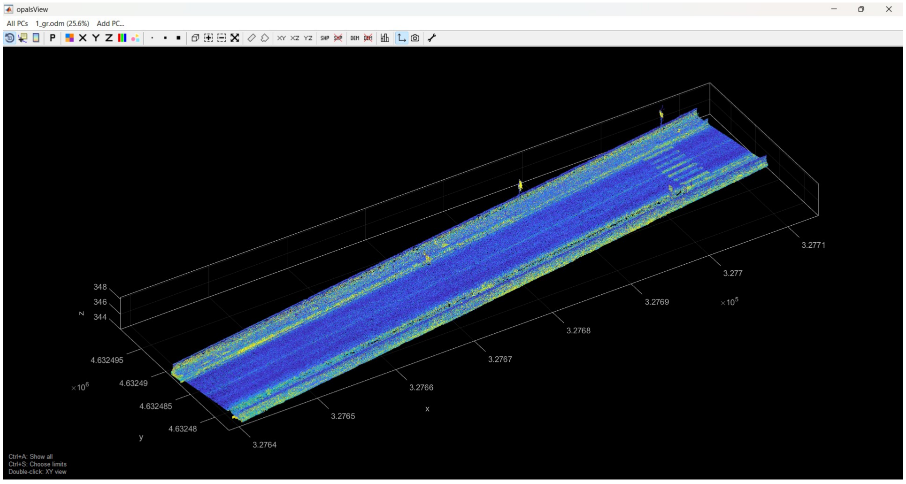


Figure 5.21: Point clouds of superstructure elements

Subsequently, to distinguish between the road surface (Figure 5.22) and the vertical accessories (guardrails and sidewalls, Figure 5.23), the workflow utilized the Echo Amplitude and the Normal Vector Z (N_z) attributes computed for each point. By setting specific thresholds for the N_z component (where values near 1 indicate horizontal surfaces like pavement, and values near 0 indicate vertical surfaces like barriers), it was possible to separate the cloud into distinct sub-sets. This procedure successfully extracted the precise position and linear extension of the guardrails and the road axis, preparing the geometric primitives necessary for the subsequent modeling phase.

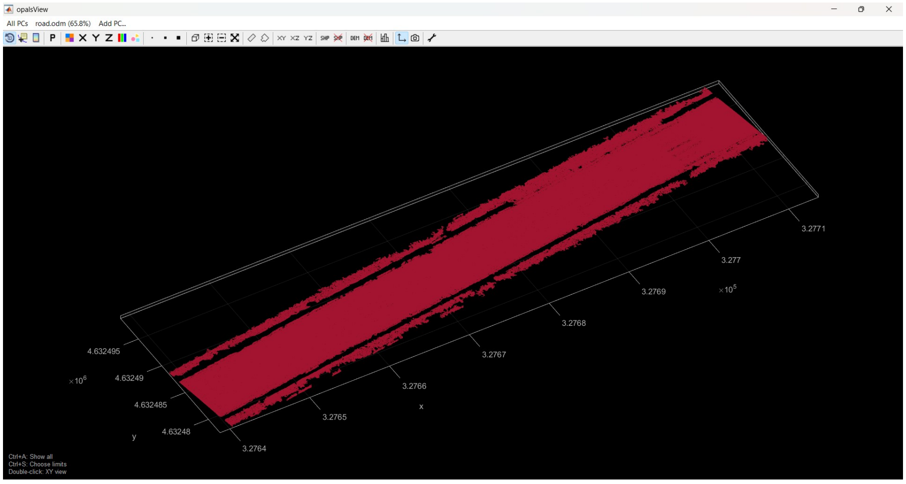


Figure 5.22: Point clouds of road surface (red)

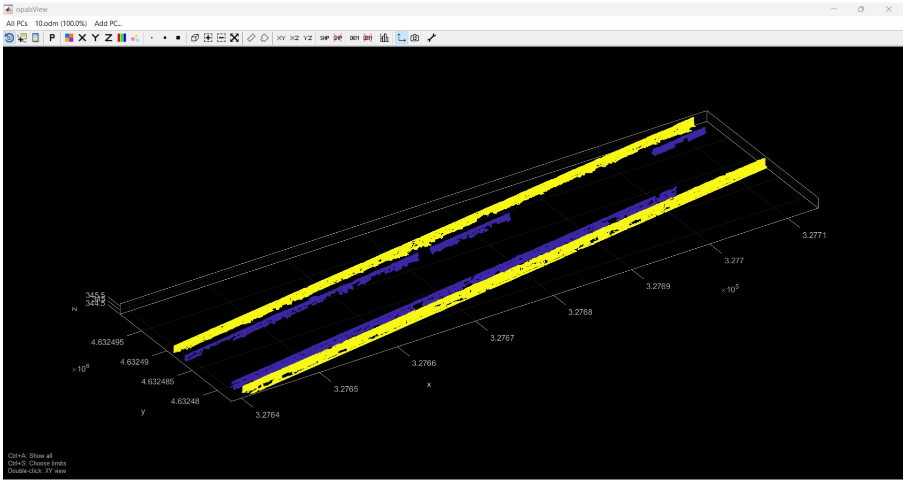


Figure 5.23: Point clouds of guardrail (violet) and sidewalls (yellow)

5.2.2 Scan-to-BIM workflow and platform integration

Following the semantic segmentation, the workflow transitioned to the Scan-to-BIM phase. Given the dual nature of the asset, acting as both a structural work and a linear road infrastructure, a multi-software approach was adopted to maximize modeling efficiency. The segmented point clouds representing the road surface were imported into Autodesk Civil 3D. Here, the planimetric alignment and the altimetric profile of the road axis were reconstructed by interpolating the cloud data, ensuring that the digital alignment adhered strictly to the existing as-built.

Simultaneously, the structural modeling of the masonry components (piers, abutments, and arches) was conducted within Autodesk Revit. Due to the geometric regularity of the bridge, the manual modeling process was replaced by an automated workflow. A Dynamo visual programming script was utilized to read the coordinates and dimensions from the segmented structural point clouds and instantiate the corresponding parametric families within the BIM environment. The combination of the Civil 3D road corridor and the Revit structural elements resulted in a comprehensive model achieving Level of Development (LOD) E. At this stage, the model represents a topologically and geometrically accurate of the physical asset.

To visually verify this geometric consistency, a direct comparison was performed between the source data and the modeled output. As depicted in Figure 5.24, the high-resolution orthomosaic derived from the aerial survey (top) is juxtaposed with the final parametric model (bottom). This alignment demonstrates the high fidelity of the reconstruction, confirming that the automated Scan-to-BIM workflow successfully captured the morphological characteristics and the planimetric layout of the infrastructure.

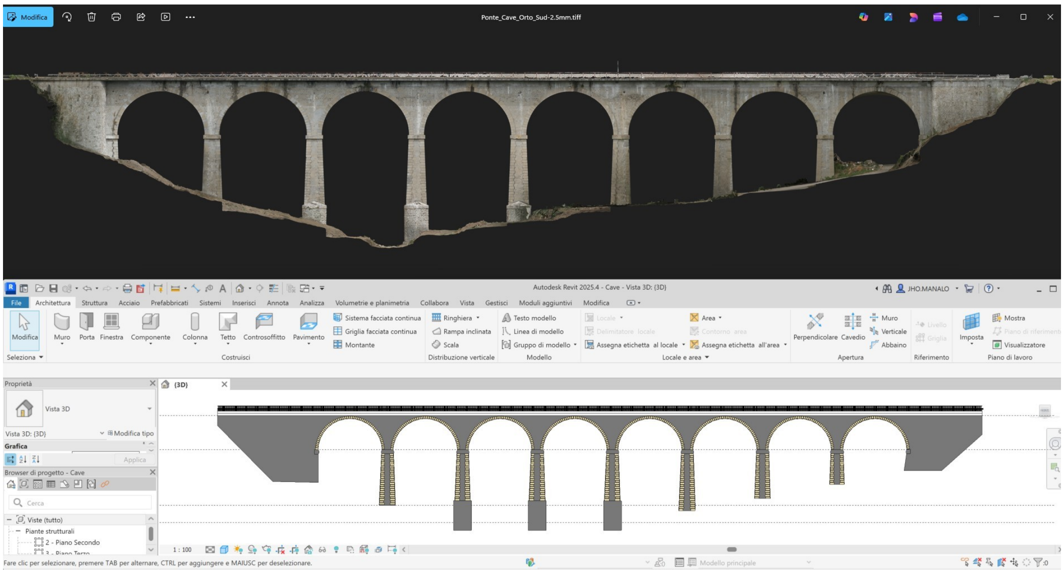


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Figure 5.24: Comparison between the RGB orthomosaic and the BIM model

As established in the objectives, the geometric model serves as the baseline for the transition to LOD G (LOD for Management/Maintenance). It is important to note that this transition does not require further geometric refinement, but rather the semantic enrichment of the objects. The model is currently being populated with maintenance data, material characteristics, and inspection records derived from the NDT analysis (including the defect mapping from the TLS intensity data), transforming the geometric replica into a functional Data Repository for asset management. The ultimate goal of this digitization process is to facilitate the seamless exchange of data across different management scales. To achieve this, the enriched BIM model was exported in IFC (Industry Foundation Classes) format, the open standard for interoperable data sharing. This ensures that the geometric and semantic information remains accessible regardless of the proprietary software used by the infrastructure manager.

The testing of this interoperability workflow was conducted within the framework of the PIASTRE research project ("Piattaforma Innovativa Adattiva per Strade Resilienti" - Innovative Adaptive Platform for Resilient Roads). The purpose of the project was to conceptualize and test the effectiveness of using such a cloud-based solution for the management of road infrastructure through the spatio-temporal fusion of heterogeneous remotely sensed datasets such as satellite images, drone photogrammetry images, LiDAR, and Ground Penetrating Radar (GPR). Within this context, the IFC model of the Bridge of Cave was successfully uploaded and integrated into the PIASTRE digital platform. As illustrated in Figure 5.25, the platform effectively interprets the semantic hierarchy of the BIM model. The interface displays the list of structural elements derived from the IFC export on the left panel, maintaining the object-oriented structure defined in the authoring software. Crucially, the platform also ingests the unstructured data associated with the model: the figure highlights how georeferenced UAV photographs are linked to their specific spatial locations. This feature ensures that the visual evidence of the asset's condition is directly accessible within the 3D environment, bridging the gap between the abstract geometric model and the high-resolution reality capture data.

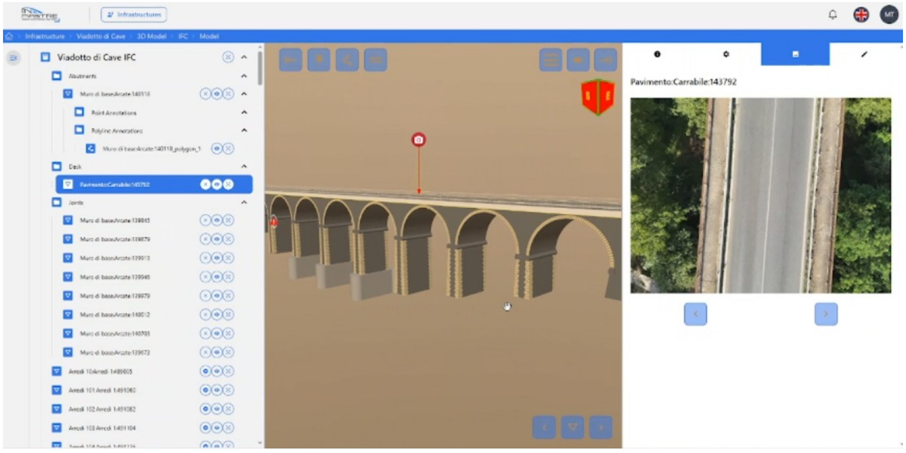


Figure 5.25: Interface of the PIASTRE platform showing the integrated IFC model

A further layer of diagnostic capability is provided by the integration of the Terrestrial Laser Scanning (TLS) intensity data. Figure 5.26 presents the visualization of surface anomalies detected through laser reflectance analysis. In this specific view, the point cloud is rendered based on intensity values, revealing areas of material degradation or moisture saturation that may not be visible in the RGB spectrum. The inset detail within the figure demonstrates how these specific anomalous point clusters have been segmented and imported into the platform as distinct digital elements. This process allows inspectors to treat the damaged area as a queryable object, enabling the direct attachment of technical comments, severity classifications, and annotations specific to that defect.

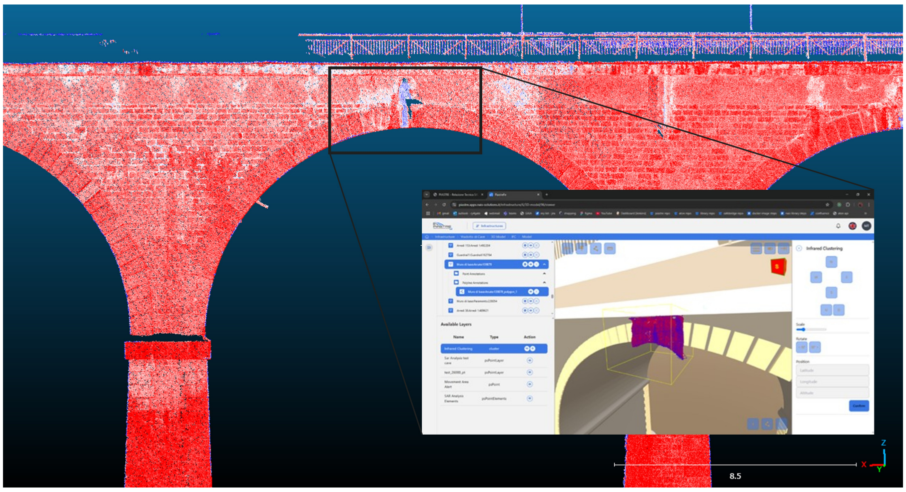


Figure 5.26: Anomaly detection via TLS intensity analysis

To further optimize the remote inspection workflow, the platform supports the creation of georeferenced alerts. This function allows the operator to place digital markers on the model corresponding to critical findings identified during the post-processing phase. A description of the process for a specific alert marker is shown in Figure 5.27. Again, the annotation history, as well as the integration of multi-spectral information, is highlighted for interest. In this case, it is shown how thermographic imagery acquired using the DJI Mavic 3T is embedded in the alert system, thus furnishing immediate verification of thermal abnormalities (for example, delaminating or water intrusion) for the precise location in which it was detected.

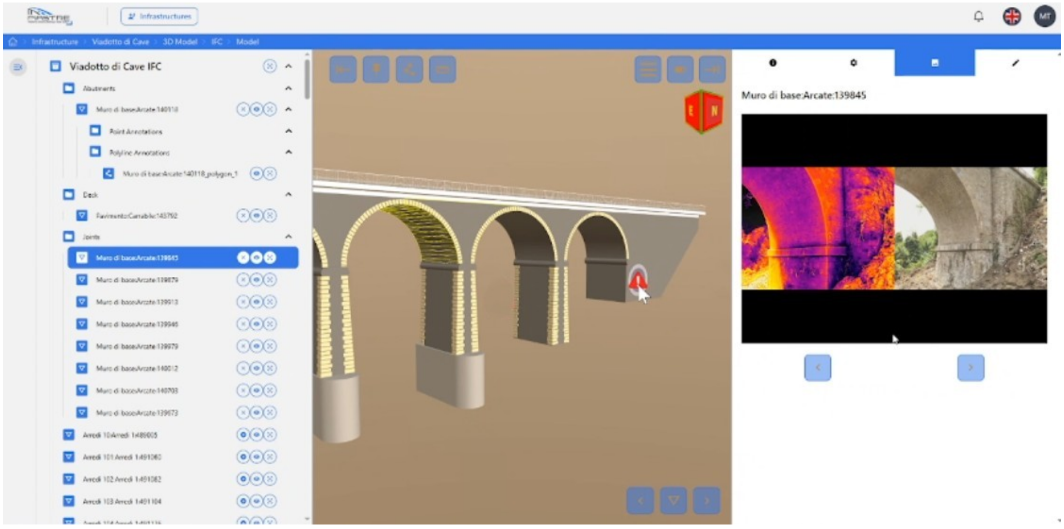


Figure 5.27: Management of Georeferenced Alerts

The implementation of the Bridge of Cave case study within the PIASTRE platform underscores the tangible benefits of utilizing a georeferenced Digital Twin as a central Data Repository. The major advantage is in the optimization of the inspection process, where, through the digital inspection carried out in an office environment, engineers can identify and assign important regions prior to physically sending out the operators to the actual site in the field. While this remote inspection cannot fully replace the on-site verification process, these efforts certainly improve the operational safety and efficiency to great lengths. The operators can accordingly be directed to the regions of interest that have been previously identified, thereby saving the time taken to stay in the risky environment. At the same time, the precise georeferencing of all the different sources of information, including the point clouds and the thermal images, provides the requisite framework for the long-term monitoring process to begin in the right way, where the upcoming surveys can easily fit in with the same coordinate framework to perform the necessary spatial and temporal analyses (four-dimensional analyses) to track the development of the defects over time, thereby switching to the predictive mode of operation instead of the reactive mode of the current process of maintenance.

Chapter 6

Conclusions

Management and maintenance of road infrastructure over the past few years have changed dramatically with the development of a new regulatory environment and an ever more complex asset lifecycle management environment. Recent ministerial decrees from Italy and the EU provide strong guidance to shift from reactive maintenance methods to more proactive digitized and predictive methodologies. Using visual inspection to assess road infrastructure has always been part of assessing the structural condition; however, using visual inspection alone has substantial limitations in regards to both efficiency and safety. The requirement for qualified personnel to work in hazardous environments, which often necessitates traffic closures or working at heights, highlights the urgent need for methodological optimisation. This research does not advocate for the replacement of visual assessments but rather proposes a synergistic approach where advanced instrumentation augments human expertise, thereby enhancing the safety of operations and the quality of the acquired data.

In response to these challenges, this doctoral thesis has focused on identifying and evaluating optimal Non-Destructive Testing (NDT) instrumentation and survey workflows. The objective was to refine standard practices to meet the digitalization targets set by national and international standards. A comprehensive literature review on NDT applications laid the groundwork for defining procedures that not only streamline on-site data acquisition but also ensure the generation of high-quality output files suitable for subsequent, off-site safety inspections. A central theme of this work is the valorization of collected data. Raw survey data, if left unstructured, offers limited insight; however, when effectively integrated, it provides a holistic definition of the infrastructure. Consequently, this research addressed the complexity of extracting actionable intelligence from mass data collection. Beyond geometric accuracy, the study explored the automation of point cloud segmentation and the enrichment of spatial data with radiometric information, such as reflectance and thermal imagery. These additional layers of information significantly extend the diagnostic capabilities beyond simple geometric reconstruction, offering a more robust basis for defect detection and condition assessment.

Crucially, the methodology transcends the isolation of survey data, channeling findings into the broader Building Information Modeling (BIM) framework. While BIM has seen widespread adoption in the building sector for design and construction, its application in infrastructure operation and maintenance faces unique standardization hurdles, particularly regarding data structuring. This thesis concentrated on the Scan-to-BIM process, shifting the focus from design-support to the accurate reconstruction of existing assets (as-built and as-is conditions). This approach ensures that the digital model serves as a dynamic repository for the infrastructure's entire lifecycle, accessible to the various entities involved in design, construction, and maintenance.

Furthermore, the research identified critical pathways for standardizing these integration procedures, providing a reference for the generation of infrastructure Digital Twins. By establishing a unified environment that synthesizes NDT data within a BIM context, it becomes possible to conduct advanced analyses that encompass not just structural health, but also operational safety. Ultimately, the components examined in this thesis, from optimized field surveys to data structuring and interoperability, should be viewed as distinct yet interconnected parts of a comprehensive management process. This integrated workflow aims to fulfill the regulatory and technical requirements for a truly digitalized approach to transportation infrastructure management.

6.1 Results

The primary analytical phase of this research focused on the identification and assessment of Non-Destructive Testing (NDT) methodologies suitable for the accurate geometric reconstruction of road infrastructures, particularly in scenarios characterized by a critical absence of historical design or maintenance data. To address this lack of information, the study established a comprehensive surveying workflow relying on direct on-site acquisition. An initial comparative analysis was conducted on the individual application of traditional instrumentation, such as Total Stations, versus high-performance reality capture tools. Although Terrestrial Laser Scanning (TLS) was effective in terms of rapid, detailed geometric scanning, it presented some real-world challenges in more difficult, complex environments. In response, the project introduced Unmanned Aerial Vehicles (UAVs) equipped with various payload instruments capable of accessing spots where a terrestrial only scanner would not, such as crossing water or scanning under a bridge, which greatly expanded the coverage of the complete dataset. The objective was not to select a single superior instrument, but to demonstrate the necessity of a multi-source and multi-scale approach. By leveraging the georeferencing capabilities of these distinct technologies, a data fusion methodology was developed, allowing for the integration of heterogeneous datasets into a unified digital environment. This synergy optimized the on-site acquisition process, maximizing the information density available for subsequent processing stages.

A significant advancement in the processing of this mass data was achieved regarding point cloud management and segmentation. Moving beyond standard noise removal and pre-processing, the research focused on extracting semantic value from the raw geometric data. Through a collaboration with the photogrammetry research group at the Department of Geodesy and Geoinformation of TU Wien, a semi-automatic process for the recognition of structural components was implemented using the OPALS software. This tool facilitated the handling of massive point clouds, enabling a rigorous structuring of the data. The result was a segmented point cloud, classified element by element, which served as the foundational input for the subsequent Scan-to-BIM phase. Furthermore, the investigation highlighted the diagnostic potential of radiometric data; specifically, intensity values from laser scanning were utilized to identify anomalous zones within the cloud, thereby optimizing the detection and characterization of surface defects and deterioration patterns.

Building upon the segmented and classified data, the research defined an optimized workflow for the as-built reconstruction of existing assets. This involved the creation of specific parametric families capable of adapting to the irregular geometries captured by the point clouds. The modeling process went beyond mere geometric tracing; it incorporated a rich set of metadata, embedding information regarding the survey methodology and the reliability of the acquired data directly into the digital elements. From the process shown, it was possible to highlight how the result from the filtered point clouds with the addition of reflectance data could be directly addressed in the modeling environment in order to define the defects based on their actual morphology. Moreover, it is essential to note that the process supports full interoperability in accordance with the standard IFC. The comprehensive workflow established in this research, connecting data acquisition to the final digital environment, is illustrated in Figure 6.1.

The experimental application of these methodology frameworks took the form of two case studies in the real world, each having their own set of challenges. The first application, concerning Ponte Sisto, addressed the complexities of operating within a dense historical urban fabric. Beyond the successful Scan-to-BIM reconstruction, a major result was the integration of the digital model into a graphic engine environment (Unity). This experiment illustrates the capability VR may have in the domain of

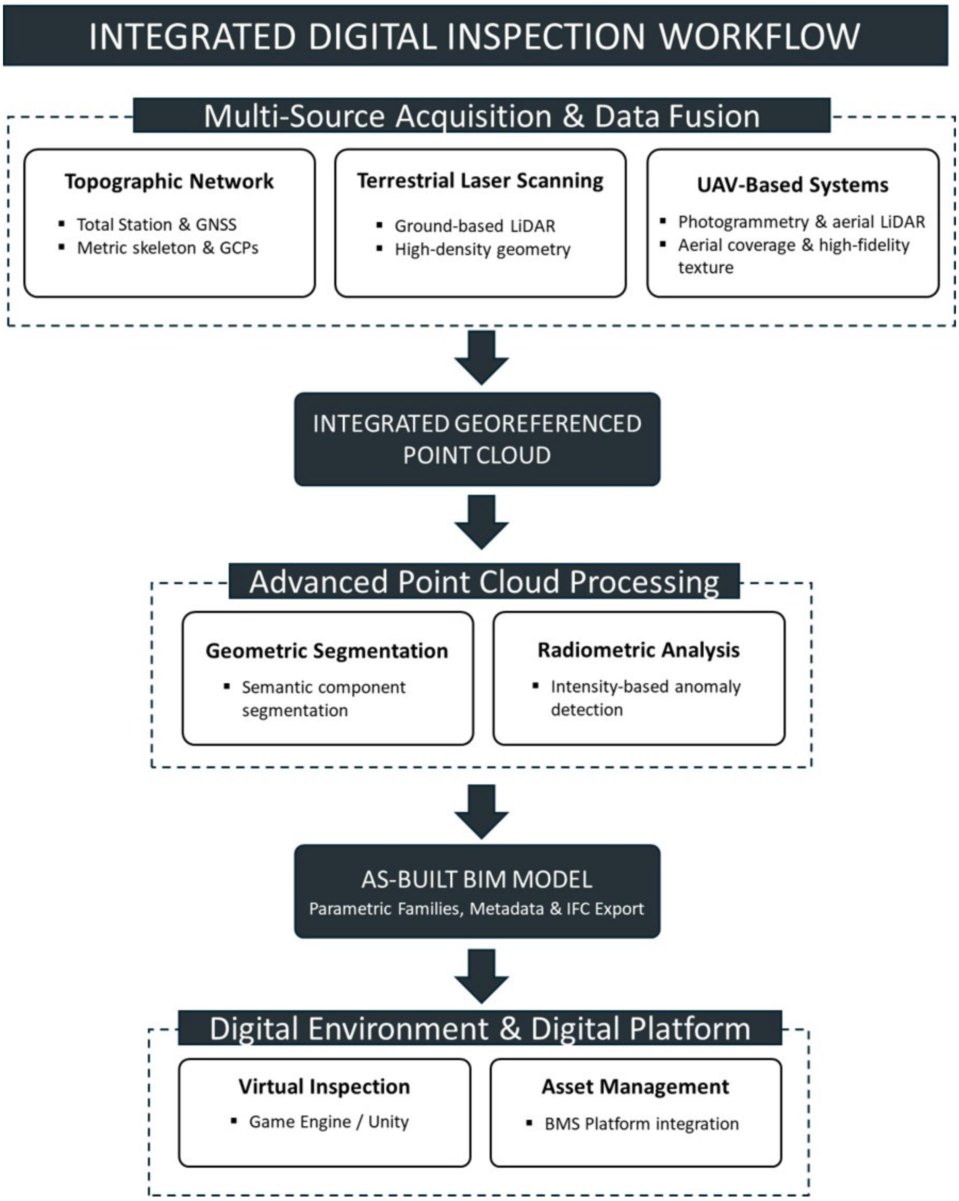


Figure 6.1: Integrated Digital Inspection Workflow

infrastructure management, as it provides a safe environment for a remotely performed visual inspection of the structure through navigation in a high-fidelity model, which would be impossible in physical circumstances, as well as the capability to carry out comparisons in the model with temporal data.

Conversely, the second case study, focused on the Cave Bridge, tackled the challenges of surveying a large-scale structure with significant height differences relative to the terrain. Here, the optimization of UAV-based photogrammetry was pivotal in complementing terrestrial data to achieve a complete geometric representation. The processing phase required a specific segmentation strategy for the road infrastructure, enabling the precise reconstruction of the pavement and structural elements within the Revit environment. The resulting IFC model served as the core component for integration into the "PIASTRE" digital platform. This implementation successfully demonstrated the convergence of multi-source data: the BIM model was enriched with georeferenced photographs, reflectance maps, and thermal imagery. This has ensured the integration of localized notifications and visualization of distress phenomena, hence facilitating the creation of a digital twin. This outcome has ensured that there is a continuous digital thread from data acquisition to asset management, which guarantees the retention of records of activities carried out in inspection and monitoring.

6.2 Digital Platforms for infrastructure management

The methodological frameworks and workflows developed in this research find immediate and practical applicability within the evolving landscape of transportation infrastructure management. As widely recognized, the digitalization of the construction sector is no longer an optional horizon but a regulatory requirement, with BIM becoming progressively mandatory for public works. However, limiting the adoption of these digital tools solely to the design phase of new constructions, or treating them merely as a bureaucratic fulfillment, would represent a missed opportunity to radically transform the sector. To truly optimize the industry, a paradigm shift is required across the entire lifecycle, leveraging the impetus of current regulations to extend digital maturity into the operation and maintenance phases. This is particularly critical for existing assets, where the vast majority of management activities take place.

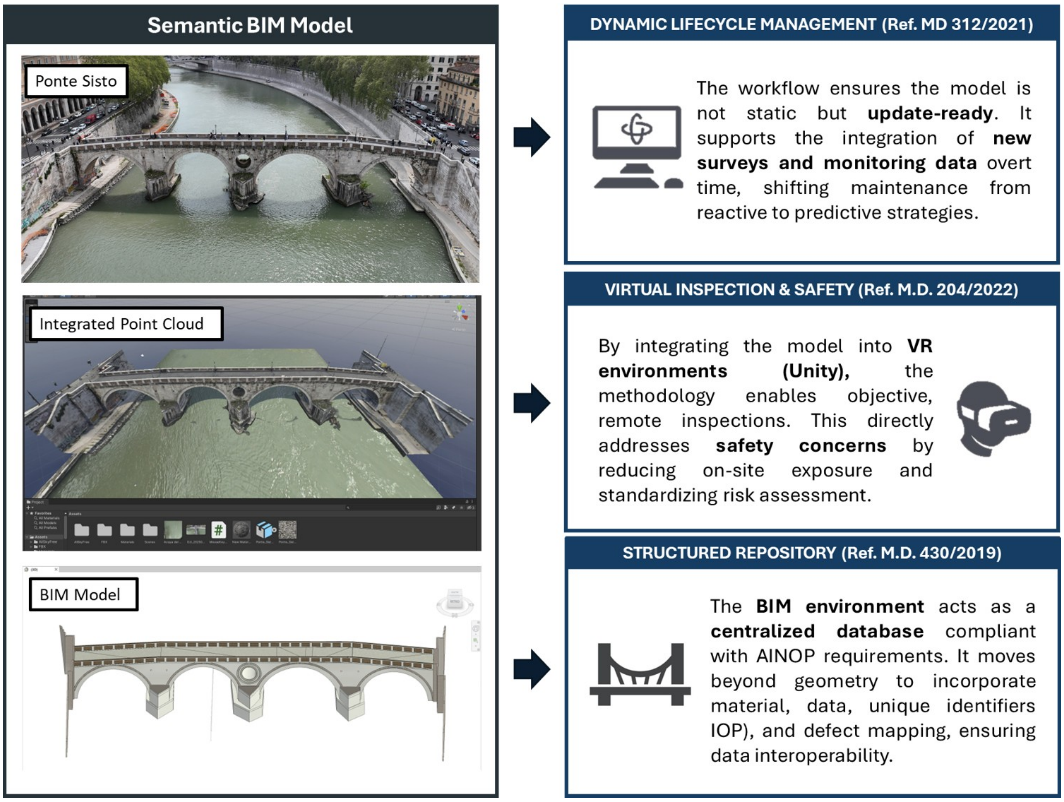
Currently, monitoring processes often rely on fragmented, paper-based documentation or disconnected digital archives. This traditional approach inherently carries the risk of data loss, particularly during the handover of assets between different managing entities or concessions. When data is not structurally integrated, the historical memory of the infrastructure is compromised, leading to inefficiencies, redundant surveys, and a lack of awareness regarding the asset's evolution over time. In this context, the proposed workflows for optimizing point cloud processing and the subsequent Scan-to-BIM reconstruction offer a robust solution. By establishing a standardized procedure for creating semantic, interoperable models, it becomes possible to lock the geometric and informative reality of the infrastructure into a format that persists beyond the tenure of a single operator.

The integration of these models into virtual environments and digital platforms represents the logical culmination of this process. From the case studies, it has been shown how the process of remote inspection in the Virtual Reality environment significantly changes the strategy concerning safety and efficiency. Therefore, the process of the initial visual observation from an actual site to a virtual one enables the operators to mitigate the risks involved in dangerous working situations like working at height or in live traffic. This means that actual site interventions can then be conducted more accurately by focusing only on designated zones necessitating comprehensive site testing.

Further, having a centralized platform to deploy data acts as the aggregator in this diverse data environment. Rather than having thermographic images, reflectance data, or geographically referenced defect notifications isolated within different software tools or storage devices, having a platform allows access to data in one place. As explored in the research, such a system allows for the comprehensive visualization of the asset, where the BIM model acts as a geometric index for all associated non-geometric data. This ensures that every inspection record, maintenance ticket, and diagnostic image is inextricably linked to its spatial location on the bridge or road segment.

Ultimately, the adoption of these digital platforms safeguards the continuity of information. It guarantees that the effort invested in high-tech surveying and data processing translates into a lasting asset for the infrastructure owner. Such an improvement from static document management to dynamic platform management builds a key foundation for such an application of National Digital Twins to develop. The proposed approach will ensure that there is data compatibility. Therefore, it paves the path towards an era of proactive management of infrastructure, which will make it more reliable, safe, and serviceable.

This alignment between technical capability and legislative intent is visually summarized in Figure 6.2. The diagram illustrates how the proposed workflow, exemplified here by the Ponte Sisto case study, effectively translates the abstract requirements of the Italian regulatory framework into concrete operational tools. By serving simultaneously as a Structured Repository compliant with the AINOP requirements (M.D. 430/2019), an enabler for Dynamic Lifecycle Management (M.D. 312/2021), and a platform for Safe Virtual Inspection (M.D. 204/2022), the developed methodology successfully bridges the gap between the physical reality of the asset and the digital compliance demanded by the National Digital Twin strategies.



DYNAMIC LIFECYCLE MANAGEMENT (Ref. MD 312/2021)

The workflow ensures the model is not static but **update-ready**. It supports the integration of **new surveys and monitoring data** overt time, shifting maintenance from reactive to predictive strategies.

VIRTUAL INSPECTION & SAFETY (Ref. M.D. 204/2022)

By integrating the model into **VR environments (Unity),** the methodology enables objective, remote inspections. This directly addresses **safety concerns** by reducing on-site exposure and standardizing risk assessment.

STRUCTURED REPOSITORY (Ref. M.D. 430/2019)

The **BIM environment** acts as a **centralized database** compliant with AINOP requirements. It moves beyond geometry to incorporate material, data, unique identifiers IOP), and defect mapping, ensuring data interoperability.

Figure 6.2: Operational impact of the proposed methodology

6.3 Future developments

The methodological framework established in this doctoral thesis, while providing a robust foundation for the digitization of infrastructure assets, opens several avenues for further research and technological expansion. A primary area for future development concerns the integration of multi-scale data sources to complement the geometric and surface-level analyses currently performed. Whereas this case study has been conducted thoroughly in high definition surveying and thermal imaging analysis to define the exterior environment of buildings, assisting data from Satellite Interferometric Synthetic Aperture Radar (InSAR) analysis is a very important next point because this integration of data will help to assess remotely the stability of ground around buildings. This macroscopic perspective is essential for managing entities to prioritize interventions, identifying structures located in hydrogeologically unstable areas before conducting detailed on-site inspections.

Concurrently, to achieve a comprehensive understanding of the asset's internal integrity, future workflows should incorporate Ground Penetrating Radar (GPR) data. As explored within the broader context of the PIASTRE research project, GPR offers the capability to investigate subsurface defects that thermal cameras may detect only partially or indirectly. By fusing GPR stratigraphy with the existing Scan-to-BIM models, it would be possible to generate a volumetric representation of the deterioration, extending the diagnostic potential from the surface to the core of the structural elements.

Furthermore, a significant advancement will be the transition from static modeling to dynamic, multi-temporal analysis. The procedures established in this work should be applied to a longitudinal case study, where the same infrastructure is surveyed at regular intervals. This would enable the implementation of automated change detection algorithms and cloud-to-cloud comparison techniques. Based on the point cloud differences that have been extracted at various intervals of time, the digital platform is able to objectively assess the drift or deformation process in terms of geometric differences.

Ultimately, to fully realize the potential of a Digital Twin, the system currently used as a storage facility for the inspection data needs to upgrade itself into a real-time monitoring hub. The integration of Structural Health Monitoring (SHM) systems, consisting of IoT sensors installed directly on the bridge, would allow for the continuous transmission of stress and vibration data into the digital environment. This relationship would enable the setting up of automated thresholds for alerting the administering party as soon as critical anomalies are detected. At the same time, incorporating real-time LiDAR scanners for traffic observations would possibly enable the virtual world to be supplemented with real-time data regarding traffic, thereby making it feasible to analyze the relationship between structural observations and traffic data. The deployment of such innovations would thereby complete the feedback loop for inspection, monitoring, and management.

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List of Acronyms

AEC	Architecture, Engineering, and Construction
AGL	Above Ground Level
AI	Artificial Intelligence
AINOP	National Archive of Public Works (Archivio Informatico Nazionale delle Opere Pubbliche)
AM	Asset Management
ANSFISA	National Agency for the Safety of Railways and Road and Motorway Infrastructures (Agenzia Nazionale per la Sicurezza delle Ferrovie e delle Infrastrutture Stradali e Autostradali)
ATZ	Aerodrome Traffic Zone
B-Rep	Boundary Representation
BIM	Building Information Modeling
BMS	Bridge Management System
BVLOS	Beyond Visual Line of Sight
CAD	Computer Aided Design
CdA	Class of Attention (Classe di Attenzione)
CMOS	Complementary Metal-Oxide Semiconductor
DL	Deep Learning
DSS	Decision Support System
DT	Digital Twin
DTM	Digital Terrain Model
EASA	European Union Aviation Safety Agency

EDM Electronic Distance Measurement

ENAC Italian Civil Aviation Authority (Ente Nazionale per l'Aviazione Civile)

FBX Filmbox

FEM Finite Element Method

GCNs Graph Convolutional Networks

GCPs Ground Control Points

GIS Geographical Information Systems

GNSS Global Navigation Satellite System

GPR Ground Penetrating Radar

GSD Ground Sampling Distance

HMD Head-Mounted Display

ID IDentifier

IDW Inverse Distance Weighting

IFC Industry Foundation Classes

IMU Inertial Measurement Unit

InSAR Interferometric Synthetic Aperture Radar

IOP Public Work Identity (Identificativo Opera Pubblica)

IoT Internet of Things

ISO International Organization for Standardization

LC Level of Knowledge (Livello di Conoscenza)

LiDAR Light Detection and Ranging

LOD Level of Detail

LVDTs Linear Variable Displacement Transducers

MD Ministerial Decree

MIT Ministry of Infrastructure and Transport (Ministero delle Infrastrutture e dei Trasporti)

MT-InSAR Multi-Temporal Interferometric Synthetic Aperture Radar

MTOM Maximum Take-off Mass

MVS Multi-View Stereo

NDT Non-Destructive Testing

NTC Technical Standards for Construction (Norme Tecniche per le Costruzioni)

OBJ Wavefront Object

OPALS Orientation and Processing of Airborne Laser Scanning data

PCA Principal Component Analysis

PIASTRE Piattaforma Innovativa Adattiva per STrade Resilienti

RANSAC Random Sample Consensus

RGB Red, Green, Blue

ROI Region of Interest

RTK Real-Time Kinematic

SfM Structure from Motion

SHM Structural Health Monitoring

SIFT Scale Invariant Feature Transform

SOR Statistical Outlier Removal

SORA Specific Operations Risk Assessment

TLS Terrestrial Laser Scanning

ToF Time of Flight

TS Total Station

TU Technische Universität

UAS Unmanned Aerial Systems

UAV Unmanned Aerial Vehicles

VR Virtual Reality

WCSS Within-Cluster Sum of Squares

XR Extended Reality

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