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A GIS-Based, AI-Enhanced Platform for UAS-Driven Railway Bridge Inspections

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Abstract

Rete Ferroviaria Italiana, part of the Ferrovie dello Stato Group and the Italian railway infrastructure manager, has developed an integrated digital framework for the structural inspection of bridges, combining Unmanned Aircraft Systems, high resolution photogrammetric surveying, and advanced data processing workflows. Central to this framework is the I.O.D.A. platform, a GIS based environment designed for storing, managing, and visualizing inspection datasets, including georeferenced and metrically accurate 3D photogrammetric models generated from UAS acquisitions. The platform is continuously synchronized with InRete.2000—RFI SAP based enterprise system for managing technical, operational, and asset information—and with DOMUS, RFI Bridge Management System, ensuring standardization of defect taxonomies and full interoperability across asset management processes.

Drone based surveys provide extensive high-resolution imagery that supports inspectors in detecting and documenting structural anomalies, though manual interpretation becomes increasingly demanding for complex structures. To address this challenge, RFI is developing AI enabled Computer Vision pipelines capable of automatically identifying and classifying defects according to the DOMUS catalogue, while maintaining human in the loop validation to ensure engineering accountability and diagnostic reliability.

By integrating UAS derived digital twins, standardized defect ontologies, and AI driven diagnostic tools within a unified ecosystem, the framework supports a shift from condition-based assessment toward predictive, risk informed maintenance strategies, advancing the digitalization of railway infrastructure inspection.

Keywords: bridge inspections, drones, photogrammetric 3D modelling, GIS based platforms, bridge management systems, AI driven computer vision.

Introduction

The morphological complexity of the Italian territory results in the national railway network having one of the highest numbers of bridges in Europe, with much of this infrastructure dating back to the late 19th century. Currently, Rete Ferroviaria Italiana (RFI S.p.A.), part of the Ferrovie dello Stato Group, manages approximately about 17,000 kilometres of railway lines and supervises roughly 23,000 bridges (including viaducts, underpasses and overpasses).

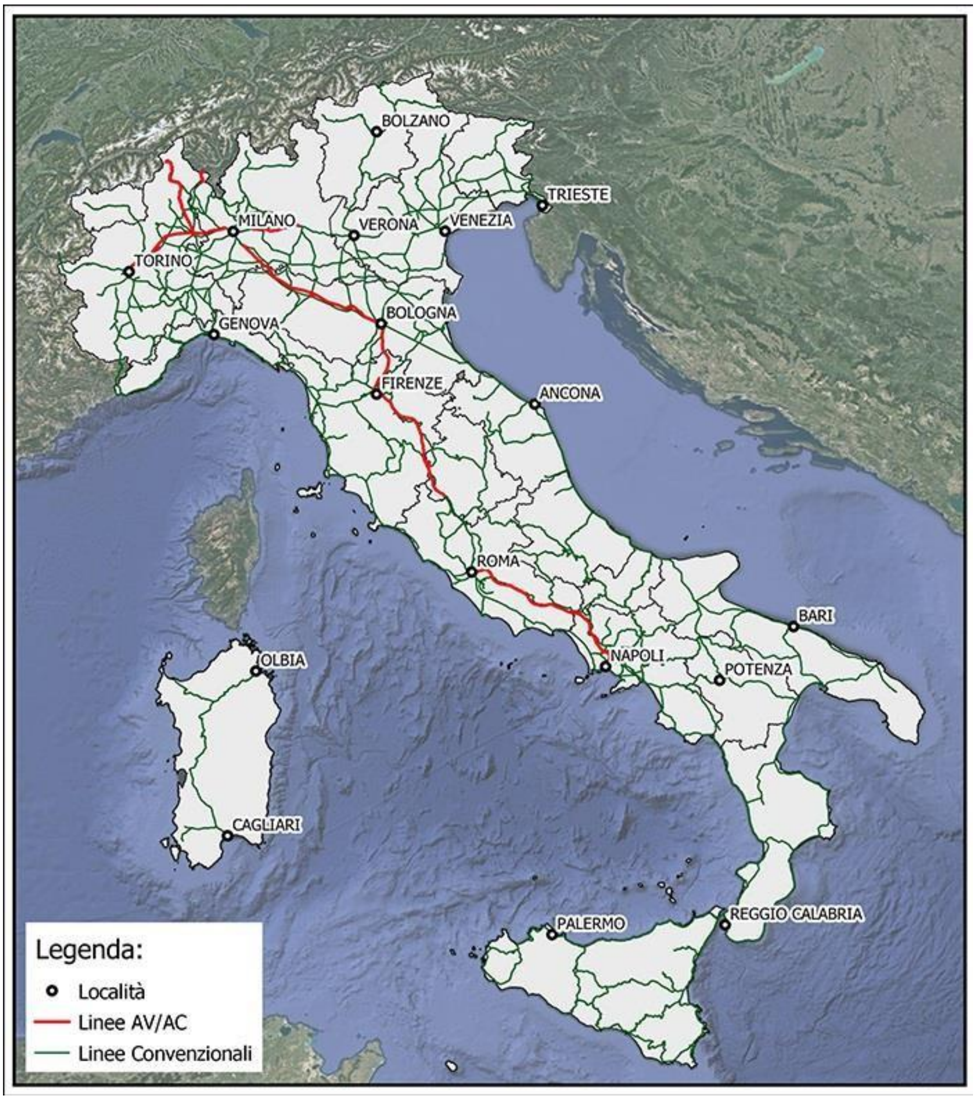

Figure 1: The Italian Railway Network

Of the abovementioned structures, 36% are underpasses, 35% bridges, 22% overpass, and 7% viaducts.

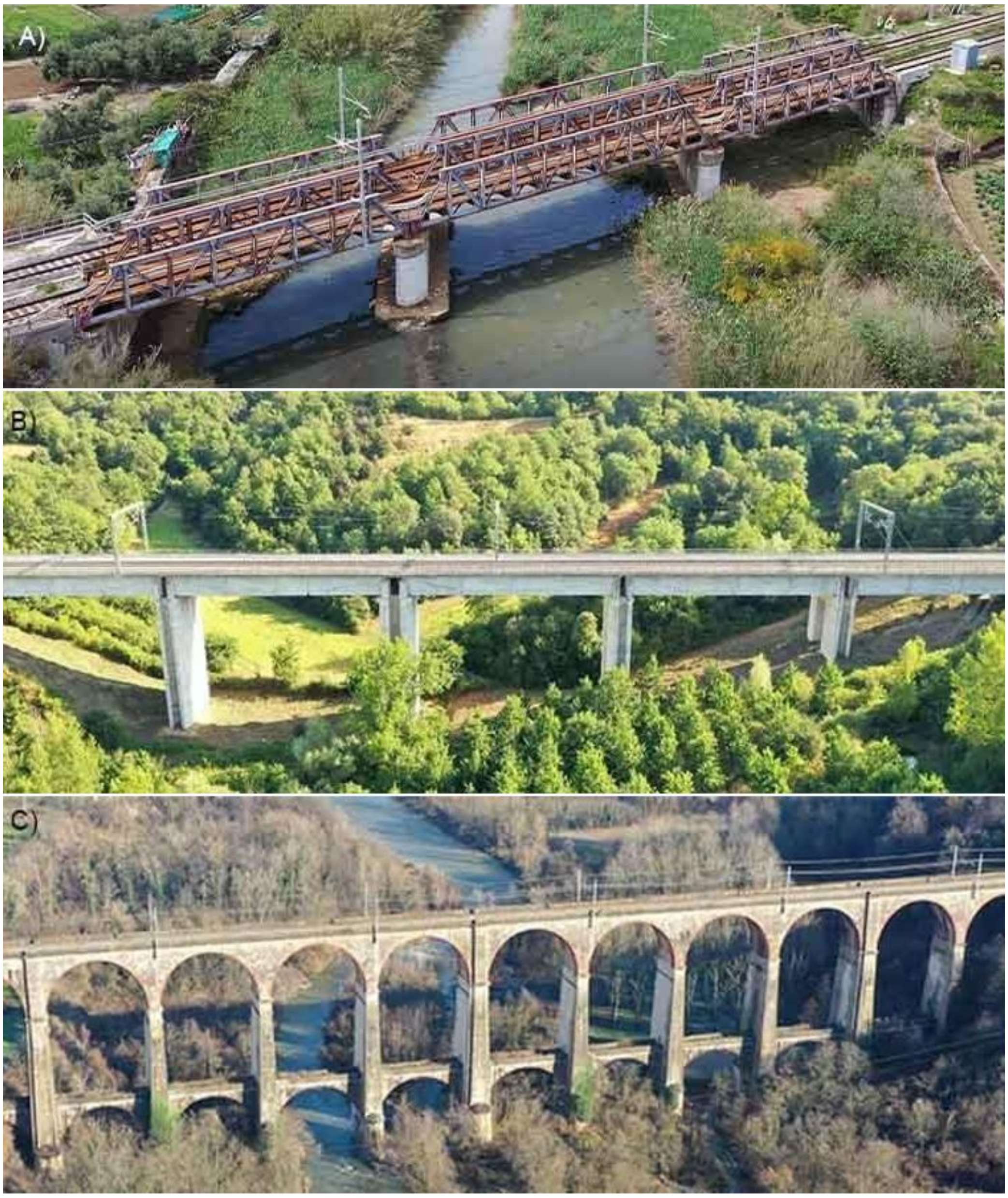

Figure 2: Examples of different types of bridges found on the Italian Railway Network: a) truss metallic deck with masonry substructures, b) viaduct with pre-stressed reinforced concrete deck and reinforced concrete substructures, c) masonry arch bridge

1 The Requirement

Railway infrastructure management requires comprehensive oversight of the network and rigorous maintenance of structures such as bridges, viaducts, and underpasses. RFI implements systematic inspection cycles, in accordance to national and international standards including IRS 70778-4 “Defects in railway bridges and procedures for maintenance” updated in 2025. These cycles comprise annual routine inspections, in-depth visual principal inspections every three years, and extensive general inspections—the most detailed ones involving the examination of all bridge components within touching distance—conducted every six-years.

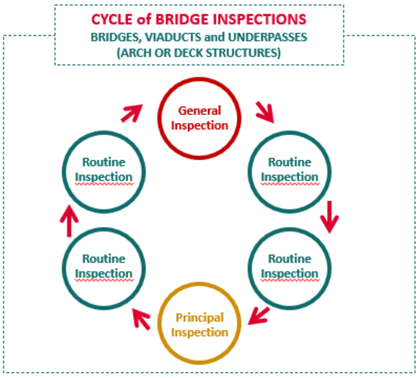

Figure 3: Bridge inspections cycle

Since 2013, RFI has updated its protocols to enhance the integrity, safety, and operational efficiency of the railway system, introducing a detailed procedure for the inspection of bridges, tunnels, and structures along with standardized methods for documenting inspection results. These protocols define the frequency, scope, and designated teams responsible for each type of inspection.

Inspection activities extend beyond the physical structures themselves and include adjacent areas, such as watercourses or embankments, that may affect overall stability or functionality. General inspections involve a thorough examination of all components—decks, piers, and abutments—often requiring specialized equipment, including lift platforms, by-bridge vehicles, boats, ladders or scaffolding to access difficult-to-reach areas. Where direct assessment is hindered or impeded by environmental barriers such as water bodies or challenging terrain, inspectors are permitted to employ UAS (Unmanned Aircraft Systems) which provide valid support to the inspection activities.

2 The Experiments

Since 2016, RFI has carried out two experimental campaigns aimed at assessing the use of Unmanned Aircraft System (UAS) for bridge inspection. The trials, conducted to evaluate the potential of this technology within inspection activities, were completed in 2021 and covered approximately 500 bridge and viaduct spans.

The results demonstrated that the use of drones makes it possible to optimize inspection times and reduce impacts on railway traffic. Moreover, these systems help to overcome several operational challenges, such as the presence of water courses, complex morphological conditions, or particular geometric configurations of the structures that cannot always be addressed using special conventional equipment (e.g., by-bridge units, elevating platforms).

The output generated by drone-based inspections also enables the georeferencing of photographic material, a defect cataloguing process consistent with RFI Bridge Management System (DOMUS), and the creation of a complete, georeferenced, and measurable 3D model of the structure.

The positive outcomes of the experimental campaigns led to a new organizational model that provides for the widespread use of drones in cyclic inspection activities. This model involves highly specialized personnel distributed across all Regional Infrastructure Operational Departments and foresees the use of drones mainly during general and principal inspections of bridges to detect structural defects. To standardize drone inspection procedures, RFI has issued a dedicated framework covering all phases—from field activities to the emission of inspections notices. Within the framework, I.O.D.A. platform assume a central role, as described in chapter 6.

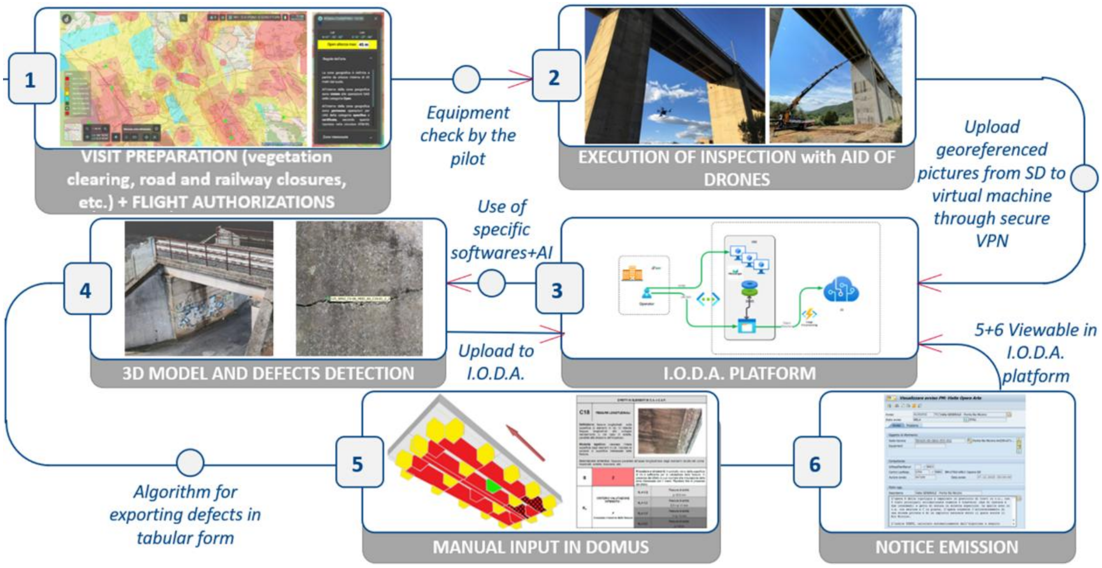

Figure 4: Inspection activities flowchart using UAS (drones)

3 Field Activities

To standardize drone inspection activities, RFI has issued a specific operational methodology that outlines the procedures for carrying out field operations.

Figure 5: Field activities, inspection of various types of bridges using UAS (drones)

Once the preliminary activities concerning the site where the bridge is located have been completed (e.g. vegetation clearing, road and railway closures, flight authorizations) and the inspection plan is established, field activities can be carried out with a coordinated approach to data gathering using UAS. These operations include lateral, nadiral, and under-deck flights, each tailored to capture comprehensive imagery of the structure's elevations and vertical elements, as well as its superstructure and overhead or vaulted components. During these flights, photographic documentation is collected according to prescribed methodologies—perpendicular for flat surfaces and radially for curved ones—to ensure precise and complete coverage. The resulting imagery and data sets are systematically catalogued and segmented according to the DOMUS system, providing a structured and accessible record of inspection results. All flight operations are conducted by certified pilots, with support from co-pilots and, when necessary, observers to ensure both safety and optimal data quality throughout the inspection process.

In detail, the following operations are systematically scheduled during on-site inspection activities:

- Lateral flights: conducted to obtain data on both elevations of the structure and its vertical components, such as piers and abutments. These flights are executed without surpassing the height of the structure's parapet.
- Nadiral flights: performed above the railway line at a safe altitude—no less than 20–25 meters from the contact line—during periods of suspended rail traffic, with the objective of surveying the superstructure.
- Under-deck flights: implemented to gather information on the deck intrados or the vaulted sections of the structure.

Photographic documentation must be captured perpendicular to the surface under examination for flat elements, and in a radial pattern for curved components, as depicted in the accompanying figure.

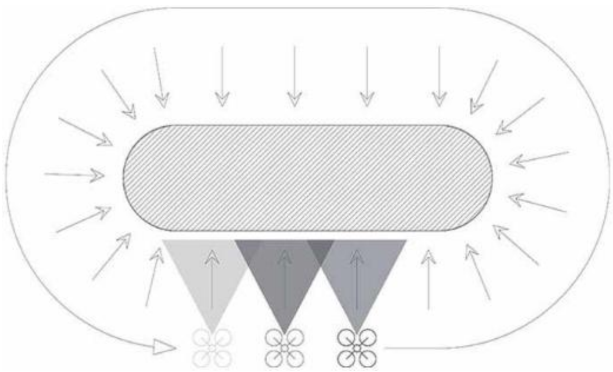

Figure 6: Schematic representation of the photographic material acquisition methodology

The results of this phase are subsequently catalogued and systematically segmented into quadrants, in accordance with the DOMUS system. All pilots are required to hold the appropriate flight certification—specifically, authorization recognized by both national and European regulatory bodies—to operate the drones typically utilized for these inspections, which generally have a maximum take-off weight of up to 25 kg. During structural inspections, alongside the pilot and the co-pilot—who assists with and remotely manages the photographic equipment settings—an observer may also be present to support the pilot and further enhance operational safety.

4 The Bridge Management System DOMUS

The Bridge Management System (BMS) constitutes an integrated framework comprising procedures, databases, and analytical models, designed to equip the railway infrastructure manager with the necessary tools to effectively coordinate and program inspection and maintenance activities for civil engineering assets, whilst duly considering both structural and operational parameters. DOMUS, in particular, has been specifically conceived and deployed for the administration of the Italian railway infrastructure since the early 2000s, and is continuously refined through systematic updates.

The core objectives of the system are:

- to catalogue and provide a geometric description of the structures subject to inspection.
- To evaluate the condition and maintenance status of the assets (specifically, their degree of deterioration or presence of defects) and to monitor their evolution over time.
- To provide information regarding the safety status of the structures.
- To establish a prioritization for maintenance interventions.

The DOMUS system is supported by a logical framework and algorithmic processes based on the following principles:

- each structure is systematically decomposed and described through a unique identification of its principal structural components, which are further subdivided into quadrants. This segmentation ensures an unambiguous and intuitive input and interpretation of the BMS system’s output data.
- The pattern of cracks and detected defects is schematically organised into defect families, thereby permitting a comprehensive and accurate assessment of the preservation state of the asset.
- Each defect, classified within a specific family and accurately located on the corresponding structural element, is duly characterised by coefficients that reflect the significance, extent, and severity of the anomaly.
- The characterisation of the safety condition, derived from the analyses performed, delineates the various criticalities and risks identified within the structure.

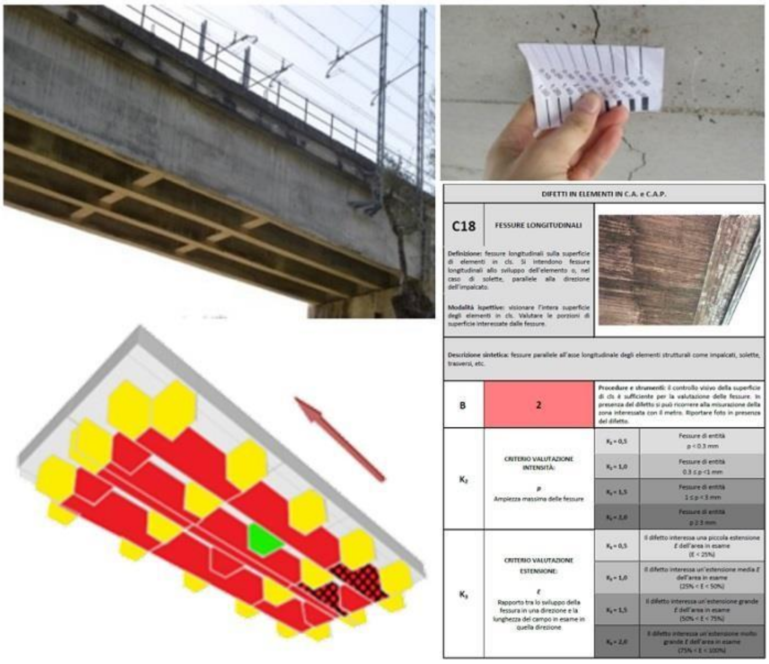

Figure 7: Breakdown into components and quadrants of the structure and schematisation of the defect identified (DOMUS system).

5 Post processing: 3D models and Material Cataloguing

The images acquired during aerial survey operations enable the generation of a measurable, georeferenced, and textured three-dimensional model of the entire inspected structure, thereby facilitating the identification of observed defects. The initial stage in constructing this model consists of the systematic cataloguing of photographic material, carried out in accordance with the schematisations and principles established by the Bridge Management System (BMS). This process is encapsulated in a "K-Plan", wherein all structural components of the asset, along with their subdivision into quadrants, are enumerated. This output supports the inspector in compiling the requisite data for subsequent BMS analyses. Furthermore, for each structural component, a dedicated hyperlink is provided to ensure straightforward access to and review of the corresponding photographic records.

The subsequent phase entails processing the catalogued data and photographic material using "Structure for Motion" software technology. This technology utilises automated photo recognition and matching algorithms to generate a point cloud of the surveyed structure. Within this cloud, every individual point is defined by its spatial position—expressed as GPS coordinates—as well as its chromatic attributes. The outcome is a three-dimensional discretisation of the object, achieved through millions of points, which serves as a fundamental element for further analyses tailored to various intended outputs, such as:

- generation of measurable, georeferenced 3D mesh models.
- Identification, quantification, and cataloguing of defects detected on the structure.
- Production of ultra-high definition orthophotos.

- Export of various views and/or sections of the point cloud, performed at specified heights and positions, which may also be used in the creation of survey graphic documentation.
- Development of digital twins through "Scan to BIM" methodologies.

Figure 8: View of Some Examples of Measurable, Georeferenced 3D Models, Output from the Post-Processing Phase

The subject of defect localization and identification is of paramount importance in the context of employing this technology for cyclic inspections and bridge monitoring. As previously outlined, these analyses are performed using software that can incorporate artificial intelligence algorithms, which are capable of integrating artificial intelligence algorithms for the automatic detection of structural defects. This capability is achieved through the application of digital image processing techniques and advanced deep learning models. Specifically, the software can segment orthophotos—derived from the three-dimensional model—into distinct sections and, within these inspected zones, systematically identify the principal surface defects observable on the structure (including, for example, exposed reinforcement, cracking, washouts, water infiltration, efflorescence, and the deterioration of concrete or masonry). These processes are guided by operator-supervised models, which also provide quantitative and qualitative assessments of the severity and extent of each detected defect.-This analytical approach offers substantial support to the technician responsible for on-site inspections, thereby facilitating a more accurate evaluation of the structural conservation status.

6 I.O.D.A. Platform

The I.O.D.A. (*Ispezione Opere D'Arte* – Inspection of Civil Works) platform, developed by RFI in collaboration with the IT company of the Ferrovie dello Stato Italiane group, has become a central element in the digital transformation of railway infrastructure monitoring and asset management. Designed to support the growing need for structured, scalable, and secure digital ecosystems, I.O.D.A. integrates a wide range of inspection data also generated by UAS (Unmanned Aircraft Systems). Its open and modular architecture enables seamless communication with systems such as

DOMUS and RFI SAP-based enterprise system, ensuring that all inspection-related information is consolidated and efficiently made available. This approach is crucial in an operational context where inspection technologies continuously produce increasing volumes of highly complex data.

One of the platform's most distinctive strengths is its advanced GIS interface, which allows the entire infrastructure network to be visualized within a georeferenced digital environment rather than as a simple list of assets. Bridges and viaducts can be immediately located on the map, each linked to its technical asset data. The system also supports the visualization of detailed three-dimensional models obtained via photogrammetry or laser scanning, enabling operators to rotate, zoom, measure, and analyses structures from angles that would otherwise be difficult to reach. This capability enhances situational awareness, facilitates comparison between different inspection campaigns, and helps with identifying the evolution of defects over time.

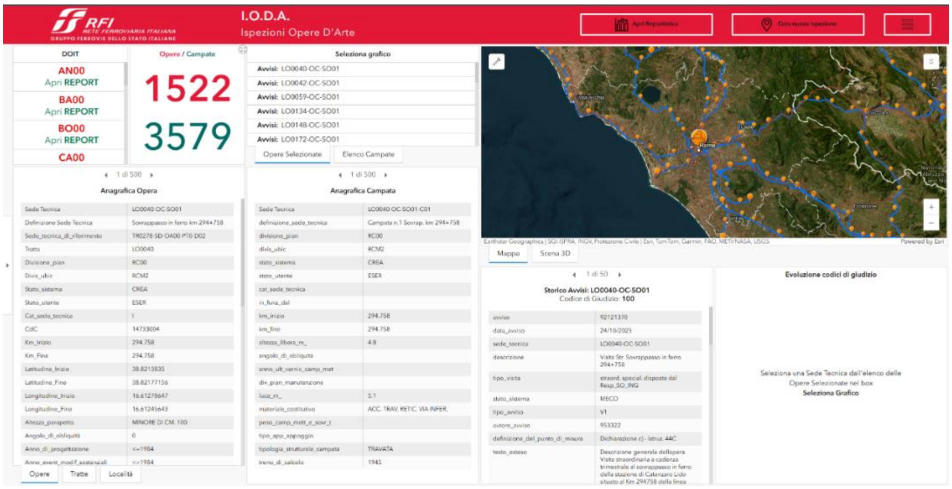

Figure 9: I.O.D.A. platform – GIS-based interactive map

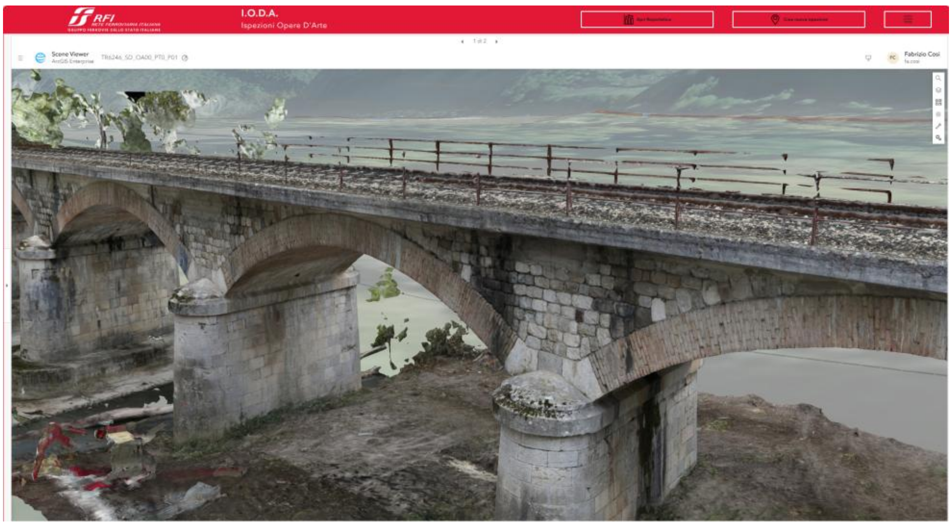

Figure 10: 3D Model of a masonry arch bridge visualized within I.O.D.A. Platform

I.O.D.A. is also fully integrated with RFI maintenance planning systems, allowing daily synchronizations of inspection information with the decision-making tools used by bridge inspectors. Thanks to Power BI dashboards and customizable reports, users can view trends, monitor recurring issues and compare asset conditions across different territorial areas, using diverse filters, e.g. location (lines, region, exc.), type of bridge, materials, type of defect observed. These dashboards act as a communication bridge between operational teams and management, improving transparency and supporting a more efficient allocation of maintenance resources.

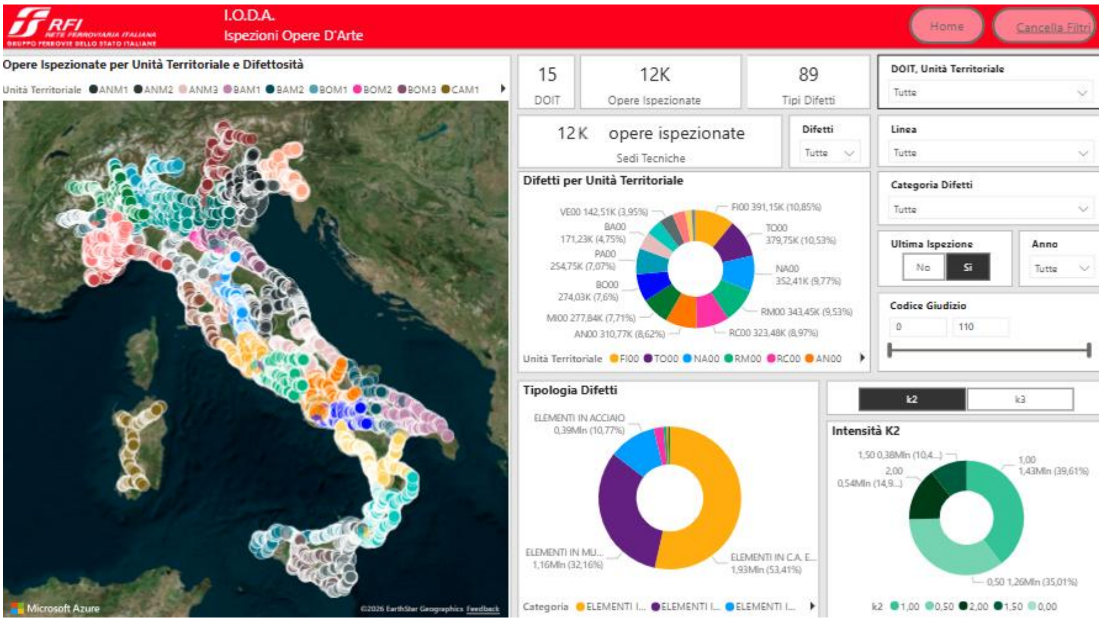

Figure 4 – I.O.D.A. platform – Power BI dashboards

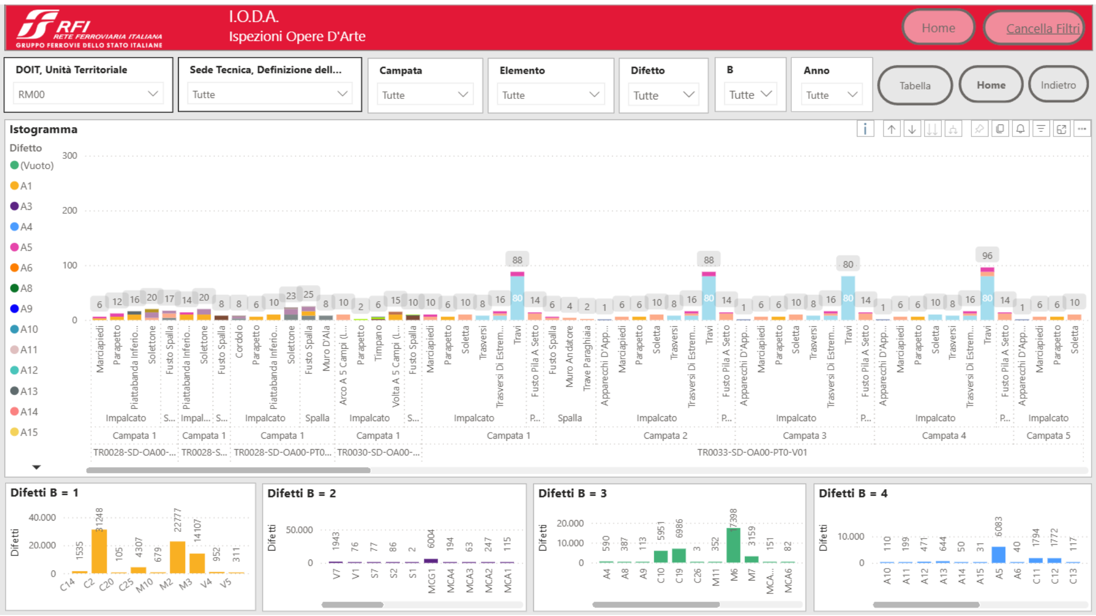

Figure 5 – I.O.D.A. platform – Power BI dashboards

A fundamental aspect of the platform is its role as a centralized digital repository, where all inspection results are stored in a structured and metadata-rich format. High-resolution images, videos, point clouds, 3D models and inspection reports are stored with precise annotations and georeferencing. This ensures rapid retrieval of historical data and enables long-term monitoring of infrastructure evolution. The platform's ability to integrate complex datasets from heterogeneous technologies makes it an essential reference point for multidisciplinary teams involved in infrastructure management.

Another key element of the platform is its scalability and future-readiness. I.O.D.A.'s architecture is designed to accommodate new modules, technologies, and data flows. This adaptability ensures the platform's technological continuity and supports the transition toward proactive maintenance strategies.

Thanks to its structured workflow, I.O.D.A. serves as a unifying tool for all stages of the inspection cycle: from planning to data acquisition, from automated analysis to reporting, and finally to maintenance scheduling. This reduces duplication, minimizes human error, and ensures long-term data integrity and consistency. Moreover, the traceability of each phase supports regulatory compliance and auditability, both fundamental elements in infrastructure management.

Overall, I.O.D.A. is not just a technological platform but a true strategic accelerator for modernizing the management of railway infrastructure assets. Its ability to integrate heterogeneous data, automate critical processes, and provide a unified and constantly updated view of infrastructure conditions makes it an essential tool for improving safety, efficiency, and long-term sustainability. Thanks to its robust architecture and compatibility with emerging technologies, I.O.D.A. enables RFI to remain at the forefront of digital transformation, ensuring that inspection processes evolve in step with new operational needs.

Together with its GIS-based mapping tools, RFI is also developing within I.O.D.A. an AI-based automated analysis functionalities to automate and standardize defect detection across the national network. Through object detection, pattern recognition, and segmentation models, the platform could autonomously detect cracks, moisture stains, deformations, and other anomalies present in images or 3D models. Each defect would be classified, prioritized, and associated with the specific asset, providing inspectors with an objective and repeatable evaluation that reduces manual analysis time. This automation not only speeds up the inspection process but also ensures consistency at the national level—an essential aspect for a uniform maintenance strategy.

RFI is developing an artificial intelligence system, presented in the next chapter, aimed at recognizing defects on bridges and viaducts across the railway network, with the purpose of supporting inspection activities carried out by inspectors, who will validate all defects identified by the AI.

7 Artificial intelligence

Artificial intelligence (AI) constitutes a fundamental element in RFI digital transformation, fundamentally reshaping maintenance and inspection activities across the entire railway network. The I.O.D.A. platform aims to incorporate AI modules capable of autonomously detecting and classifying defects—such as cracks, corrosion and other irregularities—in bridges components. These AI solutions analyse substantial datasets comprising imagery and sensor information gathered by drones, which significantly exceeds the effectiveness and speed of traditional visual inspection methods.

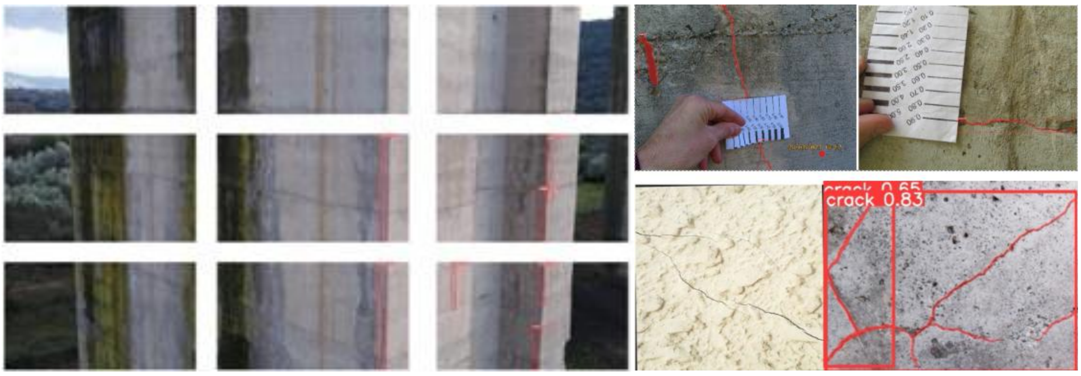

Figure 6 – AI-based defects detection and recognition system

In particular, AI algorithms such as YOLO (You Only Look Once)—a benchmark in the field of computer vision for real-time object detection—are being increasingly integrated into RFI technological infrastructure. The adoption of YOLO and analogous deep learning models facilitates the swift and accurate localization of structural anomalies within high-resolution images, whilst additional machine learning approaches, such as convolutional neural networks (CNNs), further refine the precision of defect detection and classification processes.

Within the Bridge Management System (BMS), these AI-driven techniques are standardizing the identification of defects across reinforced concrete, masonry, and steel structures, thus providing objective assessments that underpin maintenance planning and prioritization.

In aggregate, these AI applications not only automate the process of defect identification but also foster data-driven decision-making, proactive maintenance planning, and ongoing process improvement. This firmly establishes AI as a cornerstone of RFI commitment to operational excellence and the sustainable, future-oriented management of its infrastructure assets.

8 Conclusions and Contributions

The integration of advanced digital technologies is significantly enhancing RFI railway infrastructure management. AI-powered algorithms, such as YOLO and convolutional neural networks, are revolutionising defect detection and classification in bridge inspections, facilitating more accurate and consistent assessments. These systems are paving the way for proactive, predictive maintenance, which helps prevent issues before they become critical, thus improving asset longevity and safety.

The I.O.D.A. platform represents a major milestone in RFI digital transformation, providing a centralised hub for secure inspection data management and analysis. Its user-friendly interface fosters collaboration among stakeholders, while integrated

analytics support maintenance prioritisation and resource optimisation. This centralisation enhances transparency, supports regulatory compliance, and accelerates the transition towards predictive maintenance strategies.
Artificial Intelligence is also central to streamlining maintenance operations. Automated fault detection and standardised reporting using mobile applications allow field staff to efficiently record and address issues.

Overall, these innovations are driving a shift towards data-driven, proactive infrastructure management, reducing errors, and improving efficiency. Ongoing investment in AI and platforms like I.O.D.A. will further automate processes, integrate real-time data, and enhance predictive analytics, ensuring RFI infrastructure remains resilient, efficient, and ready for future transport demands.