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Digital transformation in the visual inspection of heritage railways tunnels: Technology, artificial intelligence and methodology

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ABSTRACT: The knowledge, the preservation and the maintenance of heritage infrastructures is one of the most challenging matters facing modern civilization. It involves, in inextricable patterns, factors belonging to different fields (cultural, humanistic, social, technical, economical, administrative) coupled with the requirements of safety that can be in conflict with the integrity of part of the infrastructure.

For these reasons, it is fundamental to carry out investigations and new planning strategies to know and predict the conditions of very old structures. The paper focused on heritage railway tunnels, one of the most crucial elements of the railway infrastructures in Europe.

ETS Srl introduced a new method for diagnostic of existing tunnels through multi-dimensional mobile mapping systems, and a new approach for the Management and Identification of the Risk for Existing Tunnels. The approach belongs to the digital strategies for infrastructure maintenance that are very fast and minimally invasive. The integrated instrumentation allows to have almost all the information necessary for the diagnostics of a structure with non-destructive tests, preserving the integrity of very old structures in a phase of preliminary assessment. In such a way, the process of visual inspection is automatized and back-officed. The results, in terms of defects on the structures, are digitalized and manipulated in different IT environments. The results can be incorporated in the information modelling and virtual reality inspections. The use of artificial intelligence will be necessary to speed-up the back-office phase and introduce the technologies as a new inspection standard.

A case study for the application is presented through the methodologies, including some preliminary applications of AI algorithms for the detection of water defects.

1 INTRODUCTION

Europe, the cradle of railway development, has seen its infrastructures develop particularly from the second half of the 19th century until the beginning of the 20th century. Thus, the works of art of rail networks see their average age approaching a century touching two centuries over the first lines built. Railway Infrastructure Managers therefore now have an aging park of tunnels to be maintained (Mili et al. 2021). Subject to degradation through time and the permanent interactions with the environment, the tunnel structures can face substantial maintenance and repair, the purpose of which is to mitigate the risk of incidents or even to extend its life-span (Foria et al. 2022).

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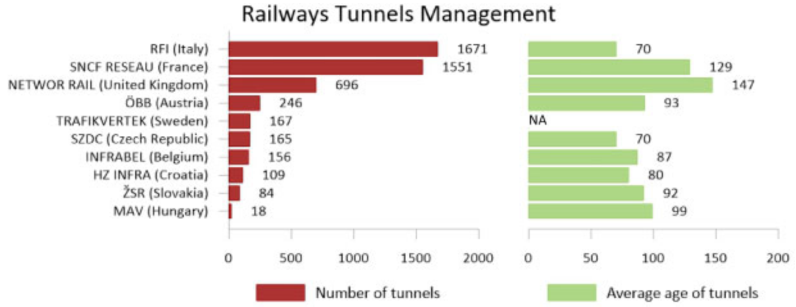

Figure 1. Number of railways tunnels managed by the main European Railway Infrastructure Managers (on the left) and average age of the same tunnels (on the right).

In Italy RFI (Rete Ferroviaria Italiana) manages 1.671 km of railway lines with an average age of 70 years and the oldest Italian tunnel is 150 years old, as shown in Figure 1.

2 VISUAL INSPECTION AND MANAGEMENT OF HERITAGE TUNNELS

2.1 *State of the art*

The planning and the management of existing tunnels and, in particular, of heritage tunnels is a central challenge for industrialized countries. The main challenge is the coexistence and collaboration of environmental sustainability and exponential technology growth. However, careful, and effective management of tunnels that involves all the stakeholders and all the activities, such as inspection, planning, design, construction, and maintenance, is not yet usual.

ETS Srl carries out the diagnostic and the maintenance of existing tunnels through multi-dimensional survey system and digital methodologies for the analysis, the integration and the management of the priorities along the tunnel.

Nowadays, the inspection of tunnels is still performed mainly by operators on the line during a partial disruption of the line (mainly during the night) or total disruption. The operator fills technical sheets following the owner's standards, national code, and practice. Generally, these forms contain general information about the tunnel (e.g., name, line, length, excavation type, lining material) and the outcome of the inspection in terms of defects detection of the tunnel structures and collateral elements. A set of photos is taken to be attached to the report showing the main compliance (Foria et al. 2021).

Even if this methodology might seem outdated with technologies available nowadays, it's still the state of the art considering that a large set of infrastructures worldwide are not checked at all.

More recent technologies allow the survey and inspection of tunnels and infrastructures with mobile mapping. Mobile mapping has the advantage of speed, efficiency, and safety reducing the time of work on the line, but brings the drawbacks of calibration, signal loss, and management of the data. However, these issues can be overcome offering multi-dimensional mobile mapping systems with different equipment in order to have a set of integrated outputs.

The current challenge in the innovation of heritage tunnel diagnostics is to enhance the quality of acquired images, developing massive data collection and processing capabilities, and analyzing the data with high-level technical experience and engineering judgment. Therefore, the automatic elaboration of big datasets is mandatory. The traditional computer vision solutions, widely developed in the industry, are not suitable to process big amounts of data in semi-supervised or weakly supervised ways. On the other hand, the supervision provided by human operators is highly dependent on the operator's skill and experience. Moreover, the operator's experience is so interdisciplinary and complex that it is unlikely to be well described by a traditional computer vision model. Besides, the learning process is an ongoing knowledge process, its transfer and reinforcement dynamics being hardly embeddable in traditional models. In contrast, the progression in machines' computational power allows solutions devised within the artificial intelligence (AI) framework to capitalize on the full precious operators' experience, efficiently applying the knowledge learnt to the collected data. Such an approach can provide a baseline for the training of new operators, thus helping in the operators' generational change.

2.2 *Methodology and technologies for the digital management*

ETS Srl has started investing in a new approach for the manipulation of the survey-inspection data to get a more objective and dynamic diagnostic, maintenance, and risk assessment to manage existing tunnels. The procedure's final aim is the Management and Identification of the Risk for Existing Tunnels (Foria et al. 2021).

The complete procedure can be defined through the following milestones (Figure 2):

- *Survey & Inspection (S&I)* with multi-dimensional mobile mapping systems to have internal geometry (laser scanner), thicknesses (GPRs), and condition of the structure (thermal and linear cameras, visual inspections, and measures). In the approach, the S&I phase can be repeated to update the data through different time steps, with this instrumentation it is possible to carry out surveys and inspections with non-destructive investigations, preserving the integrity of heritage tunnels;
- *Digitalization (DI)* of the geometric survey to obtain a 3D CAD model or IFC model;
- *Defect Analysis (DA)* from HD linear photo to map and digitalize the defects in a CAD environment. The defects are statistically elaborated and combined to obtain easy and user-friendly indexes;
- *Planning & Design (P&D):* the digital twin and the defects detection are combined in a Common Data Environment (CDE);
- *Work & Maintenance (W&M):* the maintenance and construction works are performed according to the indication of the P&D phase. The completed works are ready for a new S&I phase to determine the new condition of the structure;
- *Monitoring (MO)* is fundamental to have continuous data input through different phases, allowing a dynamic database and assessment of the structures.
- *Facility Management Platform*: an environment in which it is possible to have a complete view of the conditions of the infrastructure (e.g., geometry, geomorphological context, and risk and hazard indices, etc.). Each index value falls within specific ranges which, (e.g., with a value from 1 to 4), indicate the health of the infrastructure. The index value is not defined a priori but varies according to the aspects considered, in fact, it is possible to deconstruct it to adapt the assessment to different situations and to make it more usable by different users. Moreover, it is possible to view monitoring alerts that show the exceeding of critical thresholds.

Figure 2. Puzzle chart of the workflow (Foria et al. 2021).

The methodology is suitable for the management of heritage infrastructure. In fact, it is possible to assess, without compromising the integrity of the infrastructure, the conditions of the heritage tunnels and, consequently, plan interventions in a targeted way on the most critical areas. In addition, by repeating the process over time, it is possible to have constant monitoring of the work with the advantage of knowing the infrastructure conditions over time and catch predictive behaviors.

2.2.1 *Mobile mapping survey*

A multi-dimensional mobile mapping system adapts well to the digitalization and management of heritage infrastructure. The integrated instrumentation in fact allows to make very precise surveys, avoiding destructive investigations and minimizing the impact on working lines.

In the case of ETS srl, the system developed is ARCHITA, a multi-dimensional mobile mapping system consisting of linked and integrated equipment (Foria et al. 2019). It carries out the survey activity with an average speed of 15-30 km/h, minimizing the impact on existing lines with shortstop of the traffic and without disconnection of the electrical tension (for railway). The system can work in two different configurations (Figure 3): RAIL and ROAD.

Figure 3. ARCHITA: RAIL (on the left) and ROAD (on the right) configuration (Foria et al. 2019).

The system consists of (Figure 4):

- Laser scanner to acquire 3D point cloud;
- Linear cameras to take high-resolution photos of the tunnel lining, detecting the components and the conservation state;
- GPRs to survey the ballast thickness, status and humidity, the lining thickness, and the cavities that lie behind;
- Thermal cameras to detect and double-check defects on the lining.

The different tools are integrated and linked to each other, allowing to acquire multiple information for every single point simplifying the acquisition. Engineering experience and judgment are fundamental when processing and interpreting the huge amount of data back in the office, especially when using multidimensional surveying tools.

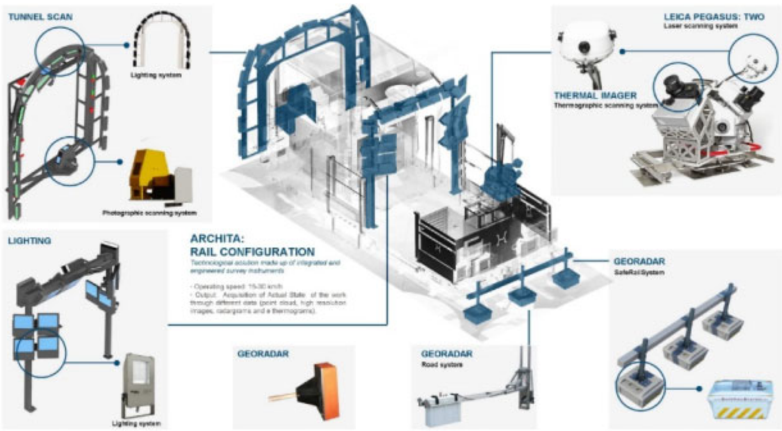

Figure 4. ARCHITA rail configuration: technological solution made up of integrated and engineered survey instruments (Foria et al. 2019).

2.2.2 *Defects analysis*

The use of measurement instruments allows obtaining more clear, objective, and repeatable data compared to traditional methods of inspections. For the defects analysis, both the manual and the automatic method (Artificial Intelligence) have been used even though the last is still under sever research and development.

For manual digitalization, a specific IT environment can process the HD images of the camera installed on the mobile mapping system. The software allows drawing both linear and areal defects thanks to the implementation of a catalog that is adapted to the specificities of the tunnel. It is also possible to associate to each defect information related to extension, intensity, and the instant of time in which the analysis is made.

The extension and intensity information is then processed to obtain indices that can be used in the different analyses (e.g., SMCA, Hazard Analysis).

For automatic digitalization, an artificial intelligence algorithm was used. A partnership between ETS Srl, Sapienza University and RMT Srl is working to obtain an algorithm capable to detect defects (Foria et al. 2021). To date, the development is focused on the use of an algorithm to detect, and segment defects related to the presence of water, cracks, and detachments in mechanized tunnels with prefabricated segment lining.

The development started from the implementation of Crack SegNet (Ren et al. 2020), with a Convolutional Neural Network (CNN) capable of automatically detecting and segmenting cracks starting from image analysis (Figure 5).

The implementation was carried out in Python and C++ using Google's Tensorflow software library. The algorithm training was carried out on a dataset of 100–1,000 images. Validation and tests on images not used in the training phase show a slight overestimation of defects by the AI, 10% more (on average) than manual detection. This overestimation was deliberately calibrated to obtain evaluations that, for the sake of safety, do not underestimate the problems of the tunnel.

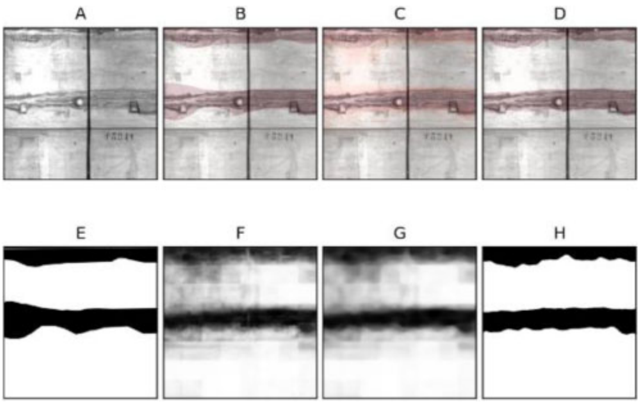

Figure 5. Example of comparison between the reference human-made annotation and the automatic annotation obtained. A – original image; B – image + human-made annotation; C – image + classification probability map; D – image + AI annotation; E – human annotation; F – classification probability map; G – blurred classification probability map; H – binarized and blurred classification probability map (Foria et al. 2021).

The use of AI for tunnels maintenance of the railway line Andora-San Lorenzo won the trust of international expert in innovation and technology who have rewarded its value inserting it among the finalist of the category "Best Use of Technology: Artificial Intelligence" at NCE TechFest 2021 in London.

Figure 6 shows a stretch of tunnel in which there is comparison between manual digitization and automatic digitization (AI) for water defects detection in mechanized tunnel (Foria et al. 2021).

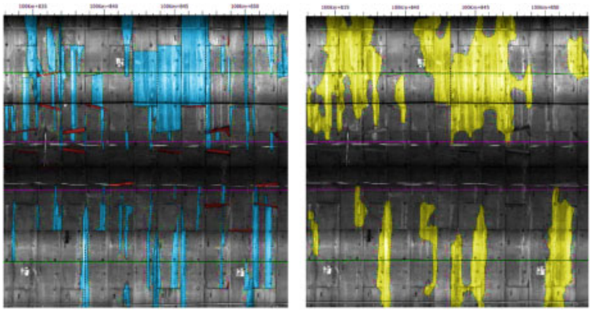

Figure 6. Manual detection (on the left) vs automatic detection (on the right) in mechanized tunnel (Railway Line Andora-San Lorenzo).

2.2.3 *Spatial Multi-Criteria Analysis (SMCA)*

In the proposed methodology, data from defects mapping are statistically processed and combined with additional parameters (e.g., geological context) that provide descriptive and analytical information about the envinronment and boundary conditions of the infrastructure. These parameters are combined through a Space Multicriteria Analysis (SMCA). It is needed when the parameter to be measured is a function of many not-directly-comparable variables, which need to be weighted and normalized (Foria et al. 2021). The use of the SMCA is essential to have a proper overview of the tunnel conditions with a structured and repeatable index (Priority Index) that combines the hazard of the phenomena and the vulnerability of the structures, to make comparisons over time and between different works. The Priority Index defines the level of attention or condition that determines the order for the management of the infrastructure elements according to their relative importance. This assessment aims at managing and identifying the risk for existing tunnels for the strategic management of resources and infrastructural assets.

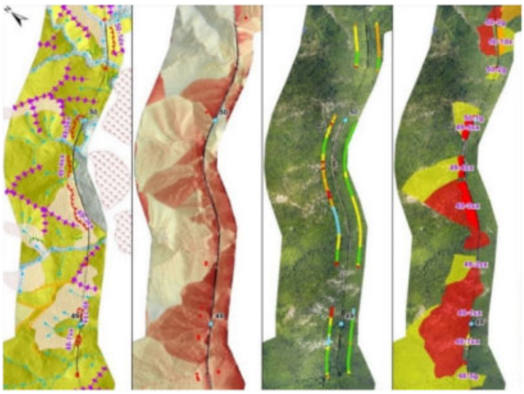

Figure 7. An example of Priority Analysis for the infrastructure management. The figure shows an application to landslide. From left to right: Geomorphological map, Connectivity index map (red dots indicate overcomes of a threshold value), Final index value, calculated every 10m along the line, on both sides, and the Hazard map (Foria et al. 2021).

This process is important to immediately highlight the critical issues and intervene promptly by identifying the causes of damages and to plan maintenance interventions effectively and efficiently (Foria et al. 2021). The priority index obtained fall within four priority classes that allow to establish which sectors have higher priority than others. This is important in the field of Facility Management to manage the budget correctly and intervene proactly. The results of this analysis can be showed in a single environment. An example in Figure 8 show of a platform currently undergoing development.

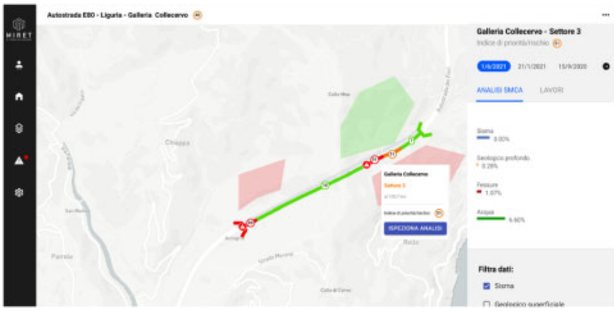

Figure 8. Priority Index of the Railway Line Andora-San Lorenzo: high priority (red), medium priority (orange), low priority (yellow), no priority (green).

3 CASE STUDY

3.1 *Galleria Sipicciano I*

The Galleria Sipicciano I is located between ch. 7+076 and ch. 7+228 of the Attigliano – Viterbo railway line within the municipal area of Graffignano (VT) (Figures 9 and 10) (Foria et al. 2020).

Figure 9. Galleria Sipicciano I – Regional Technical Cartography (CTR).

The morphological layout of the area is the result of a continuous evolution of the course of the Tiber River and its tributaries which, with various erosive and depositional cycles, has changed the tectonic depression called graben of the Tiber and the surrounding areas.

The entire area is characterized by two distinct morphological zones: the first, adjacent to the stream, mainly sub-horizontal, which extends to the hills; the second, which borders the first on both sides, consists of low-steep hills.

Figure 10. Galleria Sipicciano I: Photo of tunnel entrance ch. 7+228 (on the left) and photo inside the tunnel (on the right).

The surface drainage network has a high density, characteristic of soils with low permeability, which determine lines of impluvium incised, of limited amplitude, with torrential water circulation.

The railway line is located between approximately 115 m a.s.l and 150 m a.s.l. The maximum height of the ground level above the Galleria Sipicciano I has been estimated to be 128 m s.l.m., while the rail level has an altitude of approximately 117 m, the maximum coverage is less than 5 m.

Considering the low coverage above the structures, the poor urbanization of the area, and following the lithologies found during the investigation, it is very likely that the tunnel was built using the Cut and Cover methodology.

3.2 *Visual inspection and diagnostic*

For the survey and inspection of Galleria Sipicciano I, a multi-dimensional mobile mapping survey was performed in 2017. During the survey it was possible to obtain (Figures 11 and 12):

- High-resolution photos of the tunnel lining using linear cameras;
- The ballast thickness, status and humidity, the lining thickness, and the cavities that lie behind using GPRs;
- Thermal images thanks to thermal imaging cameras.

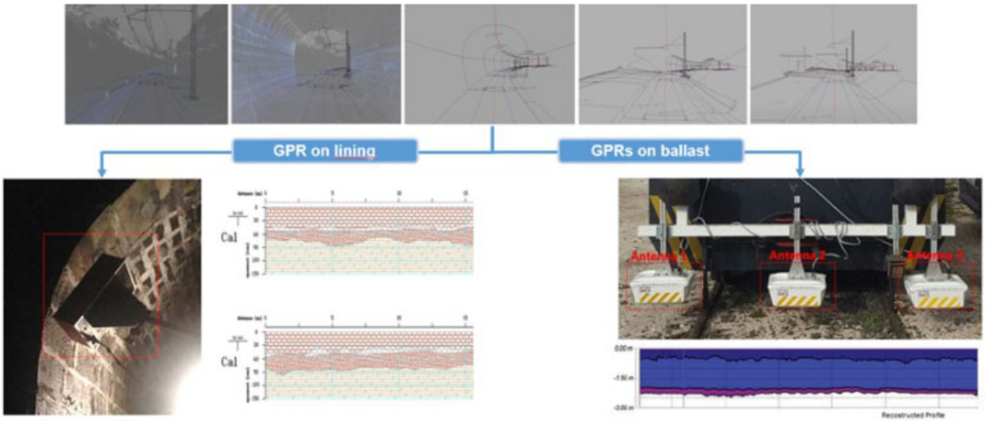

Figure 11. Tunnel digitalization through GPR on lining and ballast (Foria et al. 2019).

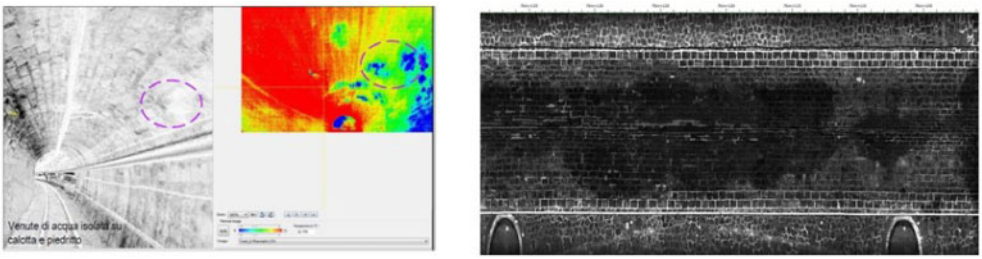

Figure 12. Tunnel diagnostic through thermal images (on the left) and HD images (on the right) (Foria et al. 2019).

For this case study, it was possible to obtain the photogrammetric profile with the use of a software, to characterize the tunnel, to identify and map the presence, extent, and intensity of any defects as described in the next paragraph (Figures 13 and 14).

3.3 *Defect mapping*

The defects mapping has been carried out through two fundamental operating tools: the catalog of defects developed for masonry tunnels and HD photos/thermal images.

This system allows to constantly monitor the conservation status of the work and evaluate the effectiveness of maintenance interventions even after years from the execution. The standardization of the analysis process also allows the comparison between different tunnels at different times (macro-scale analysis).

Moreover, the data obtained from the mapping of defects can be exported to the CAD environment and spreadsheets to be viewed and processed.

For Galleria Sipicciano I it was decided to divide the tunnel into 7 homogeneous sectors of 20 m each as indicated in the Tunnel Inspection Manual 2020 (Ministero delle Infrastrutture e dei Trasporti 2020).

After the defects digitalization, the extension information relating to defects was processed to obtain the extension index for each sector (Figure 15). The extension index is defined according to the extent of the defect with respect to sector area. The sector area corresponds to the lining portion inspected with the photo (referring to 210° of maximum photographable aperture).

These indices were then used in the SMCA analysis (3.5) for the evaluation of the priority index. In Figures 13 and 14, the results of Manual Digitalization on Galleria Sipicciano I are shown.

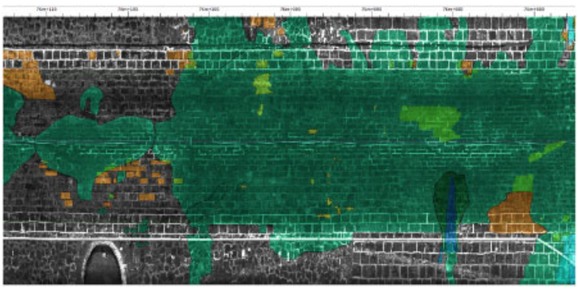

Figure 13. Defects Map (Sector 1).

Figure 14. Defects map in CAD environment (Sector 1).

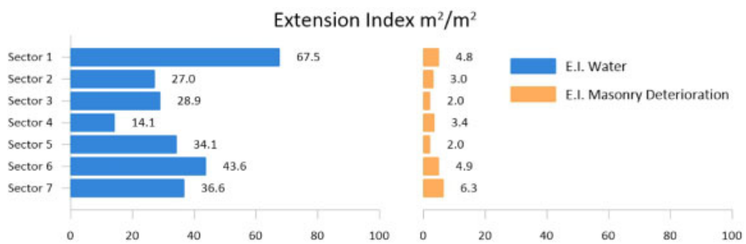

Figure 15. Extension Index: Water (on the left) and Masonry deterioration (on the right).

From the results obtained it can be seen that Sector 1 (ch. 7+076) shows a massive presence of humidity inside it due to the accumulation of water above the sector. The main causes of this phenomenon are due to the increasing slope towards Sector 7 (ch. 7+208) and to the slope discharge.

As regards the deterioration of the masonry, this is homogeneous throughout the tunnel with an increase in the entrances, in particular in Sector 7.

From these considerations we can say that the sectors at the entrances are those that need more attention.

3.3.1 *Artificial Intelligence*

Considering the positive results obtained in the use of AI for defect detection it was chosen to use the algorithm WaterSegnet (Foria et al. 2021) also in this case study.

The total area of defect digitalized manually is 1006.8 m^2 while the total area of defect digitalized with IA is 1100.6 m^2. Even if the results obtained seem good, they are not optimal, as you can see in Figure 16. This is because the algorithm, as mentioned before, has been trained on mechanized tunnels while the Galleria Sipicciano I, is a masonry tunnel. Currently, we are working on the development of an algorithm suitable for defects detection in masonry tunnel that use an appropriate neural network.

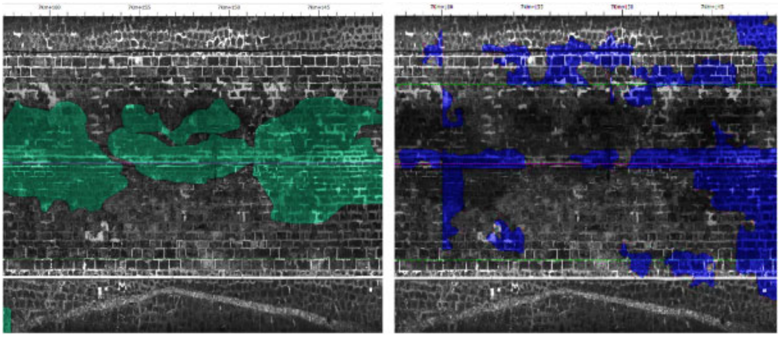

Figure 16. Manual detection (on the left) vs automatic detection (on the right).

3.4 *Digitalization*

The digitalization of the tunnel has been carried out starting from the point cloud of the laser scanner set in relative coordinates. With Autodesk Recap it was possible to process the point and to obtain the 3D model of Galleria Sipicciano (Figure 17) that served as input for the BIM modelling.

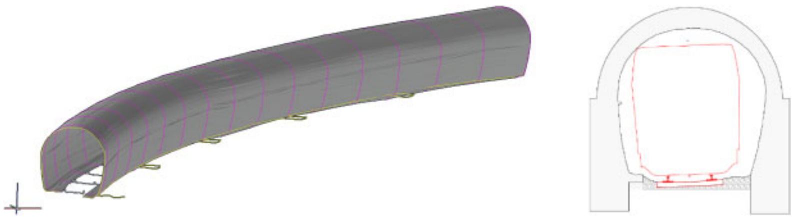

Figure 17. 3D model from geometric survey (on the left) and example of clearance overlapping (on the right): in grey the existing clearance of the tunnel, in red the clearance of the new train (PC80).

On the 3D model obtained it was carried out a dynamic clearance analysis by overlapping the clearance of the new trains (PC80) with the existing clearance of the tunnel (Figure 17) (Foria et al. 2020).

From this analysis it is possible to carry out assessments that can lead to interventions (e.g., milling or lowering of rail level) in case of interferences between clearances.

3.5 *Spatial Multi-Criteria Analysis (SMCA)*

To assess the tunnel conditions, in addition to deterioration of the masonry and water defects detected from the survey, it was decided to consider other categories that take into account the context in which the tunnel is located. A Spatial Multi-Criteria Analysis was used to combine all the categories to obtain the priority index. The SMCA allows to combine specific weights, calibrated on railway literature experience, to different categories.

For Galleria Sipicciano I, six categories were considered: Deterioration of the masonry, Water defects, Seismicity, Hydrology, Superficial Geology, Deep Geology. To have comparable analysis, it was decided to maintain the same sectors used for defect analysis. The results obtained for each sector are shown in Figure 18.

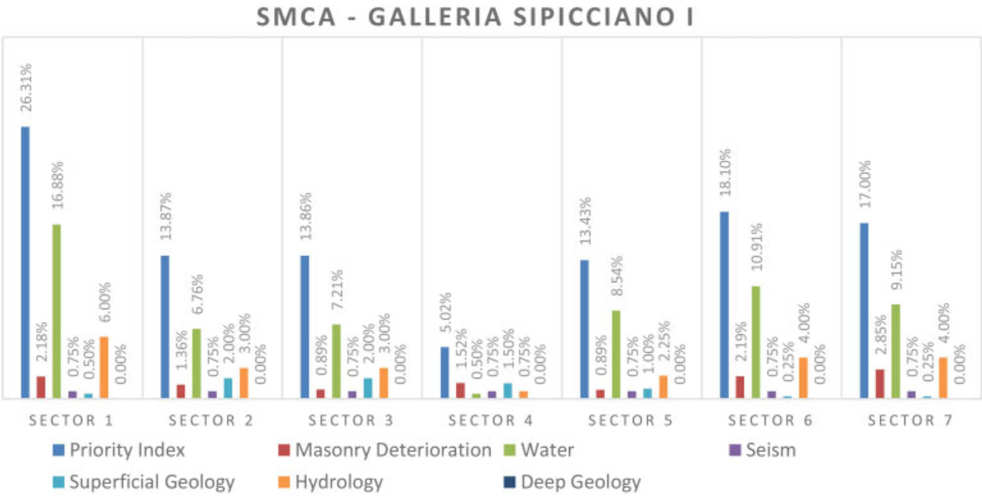

Figure 18. Priority Index.

The results obtained highlight what was shown in defect analysis. The piority index indicates a high component linked to the presence of water and hydrology,\ especially in the sections of the tunnel entrance.

In conclusion, the priority of intervention on this tunnel, barring hydraulic problems near portals and center of the tunnel, is low and the actions to be carried out must be precise and will mainly concern water disposal.

3.6 *Virtual reality for inspection*

Virtual reality is an integral part of the proposed digital methodology involving both design and maintenance of tunnel and infrastructure heritage. With this technology, it is possible to verify in real time the infrastructure conditions, acting in a timely and appropriate manner. VR's use in maintenance reduces processing times and error in diagnostic phases. In addition, the new innovative representations in Virtual Reality create three-dimensional axonometry, 3D rendering, movies and animations of the work. To assess the tunnel conditions, in addition to the analysis already described in 3.2, 3.4, 3.5 it was carried out a Virtual Reality Inspection (Figure 19). The VR inspection is aimed to verify the current state of the tunnel and allows to obtain objective geometric data and visual information available for all the parties infinitely. It is also aimed as an innovative approach for tunnel management by verifying the survey results of the investigation phase and the construction work performed.

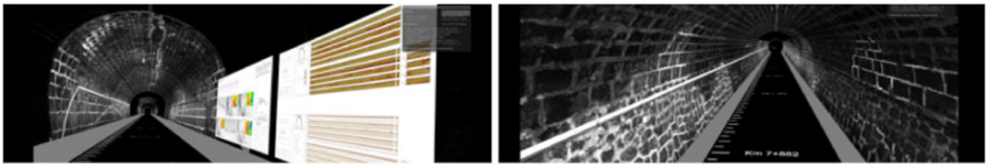

Figure 19. Virtual Reality Inspection.

4 CONCLUSIONS

The knowledge, the preservation, and the maintenance of heritage infrastructures can be carried out with new approaches. The approach belongs to the digital strategies for infrastructure maintenance that are very fast and minimally invasive.

The integration with multi-dimensional mobile mapping systems allows having almost all the information necessary for the geometries and the diagnostics of a structure with non-destructive tests, preserving the integrity of very old structures such as the infrastructural heritage. The results obtained for the case study, give a solid base for preliminary technical assessments in the management of the tunnel structures and the whole infrastructure. Moreover, these analyses are a direct input for later stage of planning, design and construction.

Within the framework of the proposed methodology (MIRET), the authors are investing in the development of Artificial Intelligence (AI) for defects detection and digitalization. The results obtained show that, to date, there are still limitations, but they can be overcome in the future developing a specific algorithm suitable for masonry tunnel.

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