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MULTIDIMENSIONAL MOBILE MAPPING AND INTEGRATED APPROACH FOR THE DIGITALISATION OF UNDERGROUND TRANSPORT INFRASTRUCTURE

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Abstract. The tunnel industry has started focusing on the maintenance and management challenges of an existing infrastructure. It is an urgent matter in industrialised countries, where the stakeholders' attention is increasing at a fast pace considering the incidents and the disruptions caused by improper monitoring and maintenance. This paper presents an innovative methodology to survey and inspect existing railway tunnels through multi-dimensional mobile mapping systems. The proposed approach belongs to the digital strategies for infrastructure maintenance. An integrated multidimensional survey system (ARCHITA) allows for collecting information necessary for the diagnostics of a structure with non-destructive tests. Linear cameras, thermographic cameras, and ground-penetrating radars acquire data to be digitalised and manipulated in different IT environments. The results, in terms of the collected data on structural defects, allow for a new approach for the Management and Identification of the Risk for Existing Tunnels (MIRET). The innovative approach aims at a smart integration of information and models for the Facility Management of the transport system. The workflow for the digitalisation and diagnosis from mobile mapping data has been implemented on two 40km-long metro tunnels.

Keywords: MIRET, ARCHITA, mobile mapping, tunnel defects, railway tunnels.

1. Introduction

The main part of European rail network developed from the second half of the 19th century until the beginning of the 20th century [1]: its average age is approaching a century and touches two centuries over the first lines built [2]. High efficiency and safety standards should be maintained; to achieve this goal, digital tools to manage infrastructure are essential [3, 4]. Particularly, railway infrastructure managers have a number of aging tunnels to be maintained [5] with increasing traffic volumes [6]. Therefore, the planning and management of existing tunnels is a central challenge for industrialised countries. Subject to degradation through time and permanent interactions with the environment, tunnel structures and technological equipment have to undergo substantial maintenance and repair tasks to mitigate the risk of incidents or to extend their service life [7, 8]. Nowadays, the inspection of tunnels is still performed mainly by operators on the line during a partial or total service disruption [9, 10]. The operator fills technical sheets by the owner's standards, national codes, and practices conducting visual inspections. 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 identified defects of tunnel structures. The primary defects consist of cracks (longitudinal, transversal, reticular, and local) and water phenomena (leakages, drops, and infiltration) [11]. A set of photos is taken to be attached to the report; the severity and extension of defects are quantified using subjective coefficients. The defects are combined to determine the hazard and the priority of interventions. This methodology is still the most commonly used, and a large set of infrastructures worldwide are not checked at all. However, more recent technologies allow the survey and inspection of tunnels and infrastructures with multi-dimensional mobile mapping and digital methodologies for the analysis, integration, and management of the priorities along the tunnel [12, 13]. A first advancement consists of supporting the inspection with instruments to have a three-dimensional (3D) point cloud (geometry) that can be texturised with images [14]. The continuous acquisition along the line makes it possible to move the activity from on-site to back-office. Defect detections can be carried out by specific software and they can be attached to the inspection or maintenance report [15]. More recent technologies allow the survey and inspection of tunnels and infrastructures with mobile mapping. These systems can run at different speeds, depending on the final precision and accuracy required by the engineering purpose. They have the advantage of speed, efficiency, and safety reducing

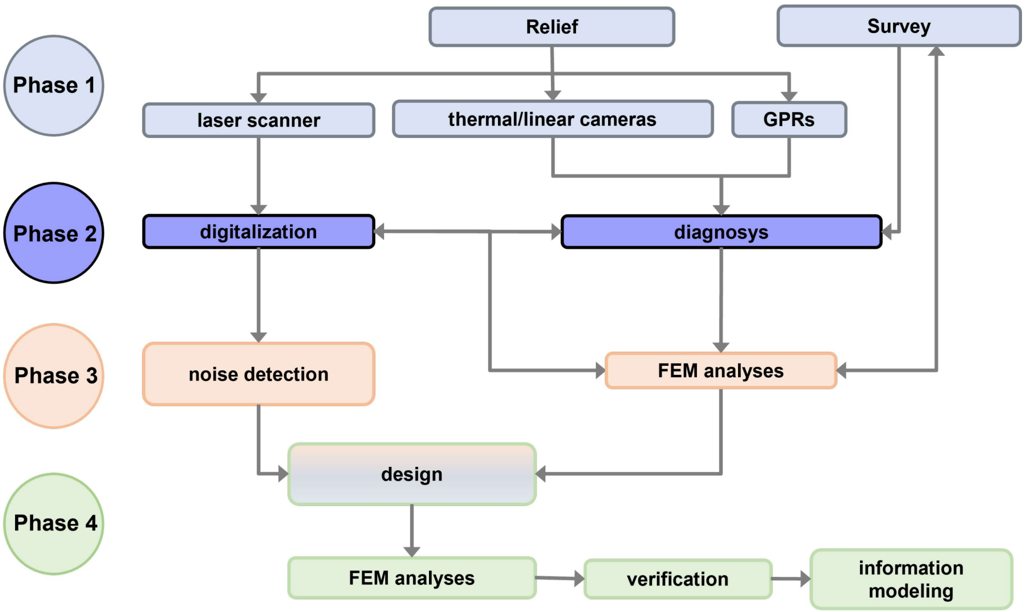


FIGURE 1. Flow chart of the MIRET workflow.

the time of work on the line to have a set of integrated outputs with a BIM approach [9]. However, the current challenge in tunnel diagnostics is to enhance the quality of acquired images, develop massive data collections, improve processing capabilities, and analyse the data with high-level technical experience and engineering judgment [16, 17]. Therefore, the automatic elaboration of big datasets is mandatory: the progression in machines' computational power allows solutions developed within the artificial intelligence (AI) framework [18].

This paper presents a methodology to carry out digitisation, inspection, and diagnostics of underground transport systems to obtain a digital model and support the decision-making process. It aims to fill and implement the collected information from multi-dimensional mobile mapping systems in an as-built model [19, 20] to be used by the infrastructure manager during the facility service life. The authors developed a BIM model to represent and manage an entire subway along more than 40 km-long metro tunnels. The results from 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 a later stage of planning, design, and construction of new railway tunnels.

2. MATERIALS AND METHODS

The proposed procedure allows manipulation of the survey-inspection data to get a more objective and dynamic diagnostic, maintenance, and risk assessment to manage existing tunnels. The aim of the procedure is the Management and Identification of the Risk for Existing Tunnels (MIRET) [21]; it is composed of six steps:

- STEP 0: *Survey & Inspection (S&I)* with a multi-dimensional mobile mapping system (ARCHITA) to carry out non-destructive surveys [22]. It allows for collecting data about internal geometry (laser scanner), thickness (Ground Penetrating Radars-GPRs), and functional condition of the tunnel lining (thermal and linear cameras, visual inspections, and measures) [23, 24];
- STEP 1: *Digitalization (DI)* of the geometric survey to obtain a georeferenced 3D model;
- STEP 2: *Defect Analysis (DA)* from high-definition linear photos and thermal photos to map and digitalise the defects in a CAD environment. Defects are identified, catalogued, and validated to obtain objective indexes;
- STEP 3: *Planning & Design (P&D)*: the digital twin and the defects detection are combined in a Common Data Environment (CDE). The current state of the tunnel environment is modelled using finite element modelling software to carry out a structural/geotechnical verification and design the required maintenance works;
- STEP 4: *Work & Maintenance (W&M)*: the maintenance and construction works are performed according to the P&D step. The completed works are ready for a new S&I phase to update the tunnel data;
- STEP 5: *Monitoring (MO)* is pivotal to have a dynamic database and assessment of the structures.

Therefore, the Facility Management Platform offers a holistic view of the tunnel conditions (e.g. geometry, geomorphological context, and risk and hazard indices). Figure 1 shows the technology workflow of MIRET.

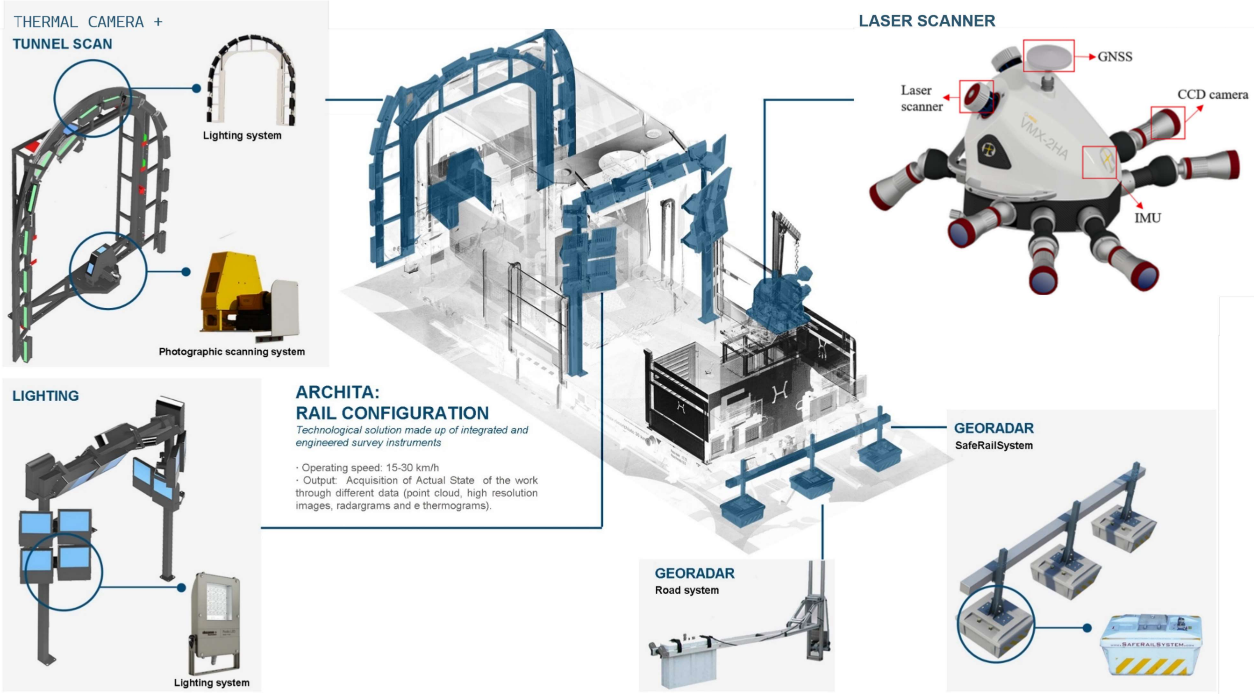


Figure 2. ARCHITA configuration.

2.1. The multi-dimensional mobile mapping system

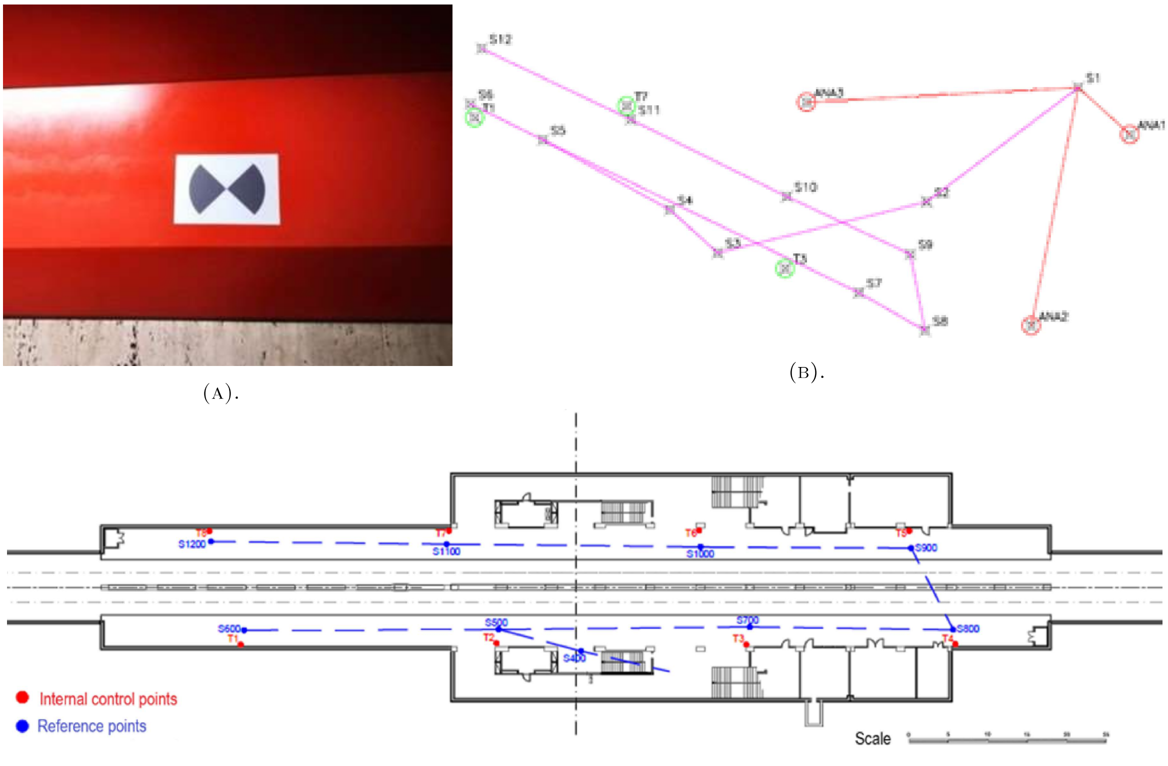
All the steps depend on the data collected by ARCHITA [22], a multi-dimensional mobile mapping system. It consists of positioning sensors (Global Positioning System, GPS), Inertial Measurement Unit (IMU), an odometer, and other survey sensors (Figure 2):

- Laser Scanner (Leica Pegasus: Two), in configuration with 8 digital cameras, 1 IMU inertial platform, 2 Z+F Profilers® 9012, 2 GPS antennas, 1 optical odometer, and 4 thermal imaging cameras. The two profilers, arranged at 30° and 60° to the axis of the binary track, allow a reduction of the masking effect due to the shadows.
- Ground Penetrating Radar (GPR) with three antennas at 400 MHz central frequency plus one antenna with 600 MHz central frequency;
- High-resolution linear cameras with image resolution beyond 10 megapixels, 1 Z+F Profiler® 9012, and a lighting system composed of 16 LED lights on a steel structure aligned with the cameras;
- Thermographic cameras with 640 × 512 pixel resolution each and lenses that offer a 90° × 70° field of view. The combination of the 4 cameras allows a full 360° ring to cover the entire image of the tunnel surface. Each thermal camera has a 70° amplitude to have enough coverage between sets of consecutive images.

2.2. Digitalization

ARCHITA uses the GNSS+IMU sensors to calculate the moving trajectory both in a relative (mobile) and absolute reference system. To analyse underground infrastructures where the GNSS signal is absent, the topographical survey is geo-referenced by using surface benchmarks near the underground stations and control points at the platforms. Since these are underground stations, it was necessary to create a topographical base for the mobile survey system. The benchmarks in the access areas outside the stations have been materialised with topographic nails fixed to the ground and they have been taken by GPS instruments (in total 3 for each underground station). Control points were located on the walls of the underground stations using topographic targets on an opaque adhesive PVC support (Figure 3a). A total station was used to connect, through a precision polygon with short sides and GPS meshes, the 3 external cornerstones to the internal control points to georeference the detected cloud of points.

Figure 3b exemplifies a scheme of the topographical points (i.e., reference points, control points, stations, and polygon) connected to the platform (purple line). In particular, ANA_i (i=1, 2, 3) are the external cornerstones, S_j (j=1,..., 12) are the station points, and T_k (k=1, 3, 7) are the internal control points. Figure 3c shows the position of all the points inside an underground railway station. In each station, ARCHITA collimates T_k and makes them available according to the two reference systems (relative and absolute). Finally, the absolute coordinates of the whole infrastructure can be obtained from the geospatial software Infinity [25].



(A).

(B).

(C).

Figure 3. (A) Opaque adhesive PVC support used to materialise the internal control points; (B) Example of a precision polygon; (C) position of all the points inside underground railway stations.

The operating speed (15-30 km·h^{-1}) of ARCHITA minimises the impact on existing railways with only a short disruption to the traffic and without the need to turn off the electrical systems.

2.3. Defects analysis

The data from the geometric survey are used to obtain a 3D model, while both the manual and the automatic method are used for the defect analysis. For manual digitalisation, a specific IT environment can process the images based on a catalogue specific for tunnels to obtain indices to be used in the different analyses. Extension, intensity, and survey time are associated with each defect to monitor its evolution. Each index value falls within specific ranges (e.g., between 1 and 4) to quantify the infrastructure condition and to allow monitoring alerts if critical thresholds are passed. An AI algorithm was used for automatic defect detection and digitalisation applying the knowledge acquired to date to the collected data. This study adopted an ad hoc library (Table 1) valid for mechanised tunnels with prefabricated segment lining. The analysed defect categories depend on the lining material:

- Masonry lining (M): longitudinal crack, transversal crack, diagonal crack, crack network, wet surface and leakages, loss of material in the joints, detachment, deformation, moss/plants presence, and efflorescence;
- Concrete lining (C): longitudinal crack, transversal crack, diagonal crack, crack network, wet surface, and leakage, detachment, deterioration, pop-out, corrosion, and exposure of rebars.

Table 1 lists the defects catalogue adopted in tunnels with concrete lining.

Masonry and water defects are treated to obtain a global index (i.e. Extension index) that summarises the current state of the tunnel lining. Its value is assessed for each tunnel sector that is about 20 m-long and is equal to the ratio between the distressed surfaces and the total lining surface (in percentage).

Moreover, the defect mapping from high-resolution photos and the point cloud allowed positioning, measuring, and quantifying of the defects identified on the tunnel lining is also carried out. The defects have been considered according to the encoder network SegNet [26] with a Convolutional Neural Network (CNN) able to detect and segment cracks starting from the image analysis (Figure 4). The deep convolutional encoder-decoder architecture for image segmentation allows the extraction of the crack skeleton and the identification of the linear defects. The implementation of the process was carried out in Python [27] and C++ [28] using the Tensorflow software library [29].

The proposed approach gave interesting results in terms of common classification metrics computed and averaged over the pixel distribution: accuracy, precision, and recall values were 93 %, 62 %, and 61 %, respectively. In particular, the automatic approach is

	Defect code	Defect name	Unit
Superficial concrete defects	C1	aggregate exposure	m^2
	C2	pop-out	m^2
	C3	exposure/corrosion of reinforcement	m^2
	C4	surface lining detachment	m^2
	C5	Wet spot	m^2
	C6	leakage from joints	m^2
	C7	leakage from cracks	m^2
	C8	freeze/thaw cycles	m^2
	C9	presence of moss or vegetation	m^2
	C10	non-homogeneous reticular cracks[1]	m^2
	C11	homogeneous reticular cracks[1]	m^2
	C12	longitudinal cracks[1]	m
	C13	transverse cracks[1]	m
	C14	diagonal cracks[1]	m
Technological defects	T12	longitudinal cracks[1]	m
	T13	transverse cracks[1]	m
	T14	corner cracks[1]	m
	T15	chipping surface	m^2
	T16	joint concrete spalling	$m \cdot m^{-2}$
	T17	misalignment prefabricated tunnel rings	m^2
Previous interventions	I18	previous structural linear works	m
	I19	previous structural areal works	m^2
	I20	previous surface linear works	m
	I21	previous surface areal works	m^2

Table 1. Defects catalogue for concrete lining, [1] cracks type I: up to 5.0 mm wide surface cracks and more than 5.0 mm cracks if they affect the lining surface; cracks type II: more than 5.0 mm wide surface cracks and side-to-side cracks.

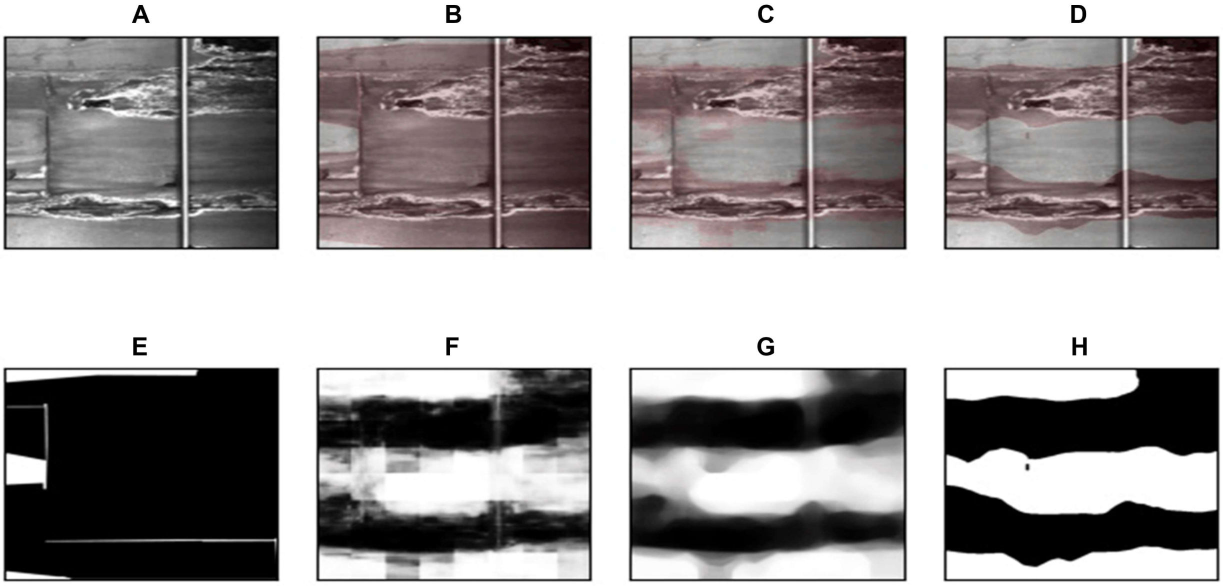


Figure 4. Comparison between human-made and automatic annotation. A – original image; B – image + human-made annotation; C – image + classification probability map; D – image + AI annotation; E – human annotation; F – classification probability map; G – blurred classification probability map; H – binarised and blurred classification probability map.

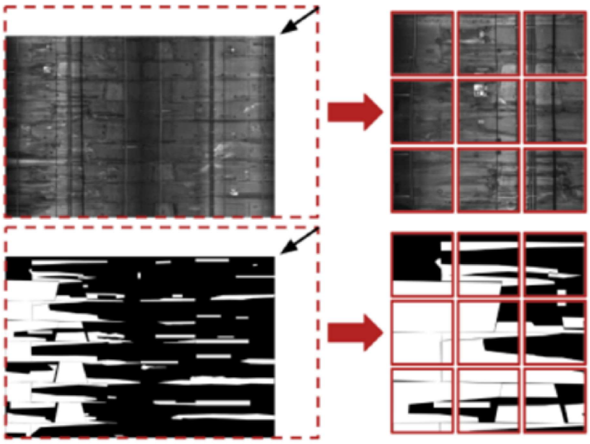


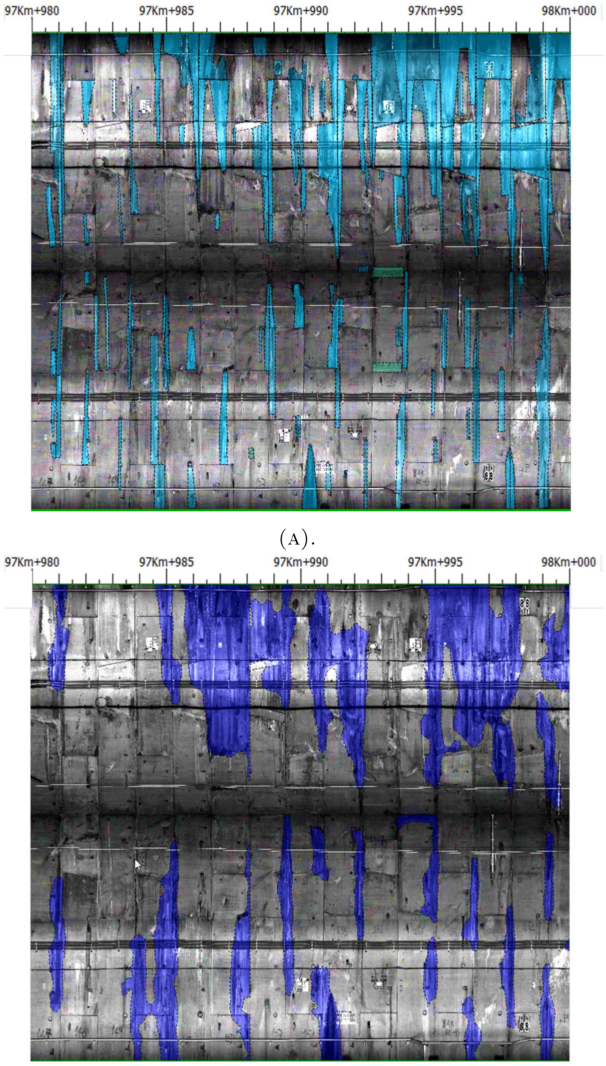
Figure 5. Example of final tiles of an original image and its mask.

more reliable when defects are simple and in isolation, while the human contribution is pivotal for complex feature overlaps: human supervision is necessary to interpret images from the tunnel inspection.

The image's resolution depends on the ARCHITA speed and the distance of the lining from the cameras: 1 × 1 mm^2 pixel size is possible when the mapping system does not exceed 15 km·h^{-1} and the surveyed surfaces are less than 5 m away. A dataset of 500 images each with a resolution representing different portions of the whole infrastructure, has been considered to carry out the automatic algorithm able to detect water defects. The images were provided with a .json file that specifies the (x, y) coordinates of the polygons containing the identified defects and damages. All the polylines containing the individual defects allowed drawing image masks using a rasterisation algorithm. The mask is a black-and-white image of the same size as the original one whose white pixels identify the areas containing the labelled defects. As a final result of this process, 500 masks have been obtained. Both the images and the masks need resizing and cropping because they were too large and multiple defects were in each image. Firstly, all the images and the corresponding masks have been resampled to 12.5 % of their original resolution; then, 320 × 320 tiles by setting an offset of 6 % of the tile size have been obtained (Figure 5). Issues coming from border effects when trying to segment cropped images have been overcome using redundant parts from larger image tiles and reducing them before combining again.

The dataset was divided into train and test sets; the comparison between train and test images shows a slight overestimation of defects by AI, on average 10 % more than the manual detection.

Figure 6 compares manual (Figure 6a) and automatic digitisation (Figure 6b) for water defects in a mechanised tunnel.



(A).

(B).

Figure 6. Manual Detection (A) vs Automatic Detection (B) in a mechanised tunnel.

2.4. Planning & Design

In this study, data from defect mapping have been statistically processed and combined with additional parameters (i.e. structure performances, seismic hazard, and geological data) that provide descriptive and analytical information about the boundary conditions of the infrastructure. Finally, a Space Multicriteria Analysis (SMCA) [30] gave a proper overview of the tunnel conditions with the Priority Index (PI). It 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. It is a structured and repeatable index that takes into account the hazards and vulnerability of the structures over time and under different conditions.

Figure 7 shows the priority layout for an existing tunnel, where different values of the final indexes

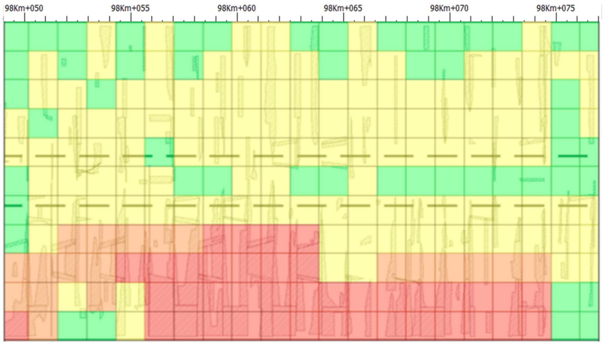


Figure 7. Priority analysis for tunnels. Green=Priority 0, Yellow=Priority 3, Orange=Priority 2, Red=Priority 1.

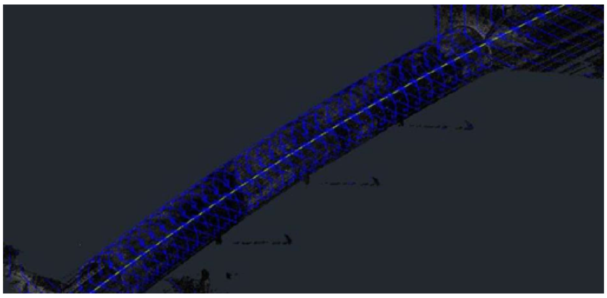


Figure 8. Progressive sections on the point cloud in 3DReshaper [31].

have been found: green, yellow, orange and red areas highlight the increasing level of risk from minimum to maximum, respectively.

In this study, the MIRET platform was implemented to survey two metro lines. Three-night disruptions of the railway traffic allowed a geometric and photographic scan of the infrastructure to be managed. The automatisation of the process is the basis for the comparison of multiple inspections to implement risk assessment, integration with monitoring and predictive maintenance during the service life of the facility. In particular, the periodic surveys shall be scheduled by the infrastructure manager based on the age of the structure, its structural properties, the length, the environmental conditions, and the traffic.

3. Results

3.1. Digitalization

Processing of geometrical data and images from ARCHITA allowed extracting a sequence of sections, to improve and optimise information (Figure 8).

Data from the geometric survey were used to obtain a 3D CAD model and an IFC model. Given the point cloud, GEDO Scan Office 2.0 [32] returned 3D polylines of the railway track and the 3D Reshaper software [31] returned a mesh from the point cloud and 3D polylines from the elements along the investigated underground line. The georeferenced digital radiometric images from the thermographic survey [33] were directly synchronised with the cloud of points obtained from the laser scanner. High-resolution linear images and thermal images permitted to evaluate the tunnel condition and digitalise its defects. Data from GPRs gave the ballast thickness, condition and humidity, the lining thickness, and the void between the soil and the lining. The methodology allowed digitalisation of the overall geometry of the infrastructure including the rails and fastenings (i.e. sleepers), tunnel lining, station structure, platforms, and walkways.

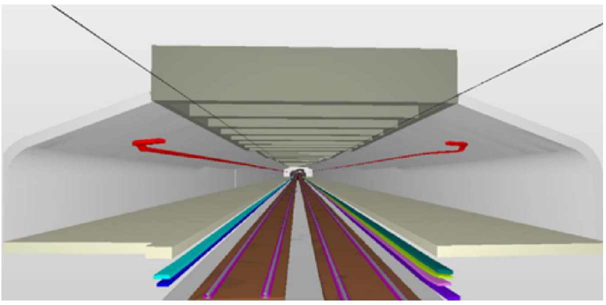
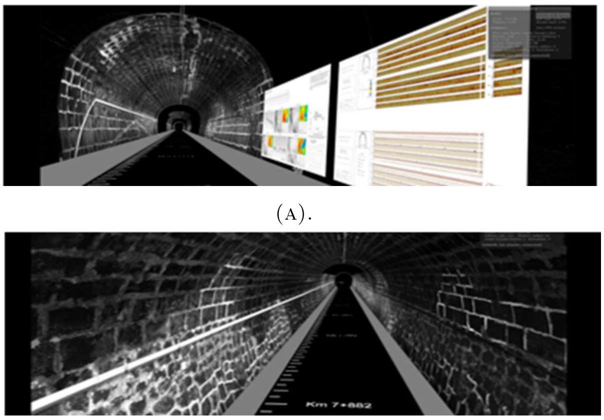


Figure 9. 3D model of a surveyed station in Solibri.



(a).

(b).

Figure 10. Virtual reality inspection. A) objective geometric data; B) visual information.

The geometry of the tunnel is obtained in an absolute reference system by integrating the odometric measurements on board ARCHITA and the control points at known coordinates connected to the external reference system.

Moreover, by using the 3DReshaper [31], it is possible to digitise the overall geometry of the infrastructure including rails and fastenings (i.e. sleepers), tunnel lining, station structure, platforms, and walkways. Figure 9 shows the final model obtained using the software Solibri [34]: it is possible to distinguish rails, fasteners and sleepers (i.e. brown, pink and grey longitudinal surfaces), civil works (i.e. grey surfaces of tunnel lining and yellow surfaces of platforms), lifelines and systems (i.e. cyan, blue, and green), and hydraulic fire system (i.e. red longitudinal lines).

Moreover, virtual reality permits verifying, in realtime, the infrastructure conditions and obtaining objective geometric data and visual information (Figure 10).

Figure 11. Detachment of concrete cover and exposure of the rebars (yellow area).

3.2. Defect Analysis

Moreover, the high-resolution photographic survey allowed the identification of lining defects that overlapped with the tunnel geometry. During the post-processing phase, the acquired data are referred to the real progressive of the railway line, thus allowing a precise location of the detected defects (Figure 11). For each defect, its location, areal or linear development, and category have been recorded according to the adopted defect library (Table 1).

High-resolution linear images and georeferenced thermal images permitted us to evaluate the tunnel's condition and digitalise its defects. Figure 12 shows water defects in blue areas; Figure 13 left and right compares HD-resolution images with thermal images whose surface temperature ranges between 18 °C (i.e. blue areas) and 24 °C (i.e. red areas): the red arrow between Figure 13 left and right) indicates water defects.

3.3. Planning & Design

The outputs from the laser scanner and the thermal survey are synchronised and can be overlapped to identify the areas/stretches with a high content or a high extension of leakages and wet surfaces, platform or ballast erosion due to leakages or wet surfaces, and water retention in the track ballast. In particular, for each tunnel sector, graphical drawings and summary tables provided the defect mapping.

Figure 14 represents defects on a tunnel segment approximately 150 m in length. The tunnel lining is represented with details about the progressive, the track position (i.e. even or odd), and its elements (e.g. piers and cap). All defects are divided into categories and other important elements or previous works on the tunnel lining are pointed out (e.g. ribs, sealing, and painting).

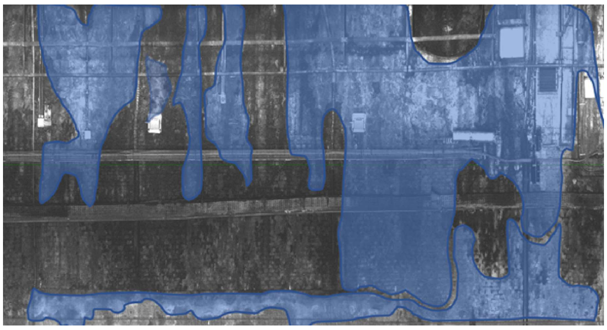


Figure 12. Water Defects detection (blue area).

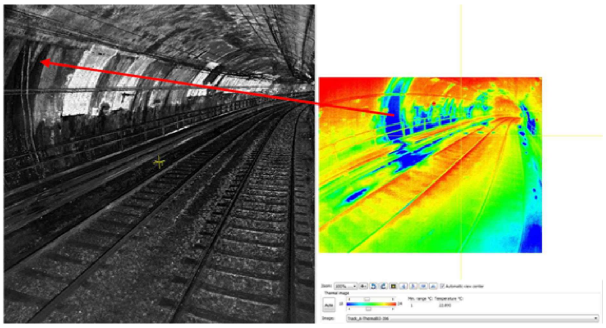


Figure 13. Comparison of HD-resolution images (left) and thermal images for defect detection (right).

3.4. Work & Maintenance

After the digitalisation, the extension index (E.I.) for each defect along the tunnel sectors has been calculated, it is the ratio between the extent of the defect and the inspected sector area. As an example, Figure 15 represents the EI values obtained for 14 sectors.

Moreover, in this study, the AI has been used for defect detection: the total area of manually digitalised defects is 1006.8 m^2 while the total area of AI digitalised defects is 1100.6 m^2: false positives were 19.8 %, while false negatives were 10.5 %. Such differences highlight the need for a further calibration of the algorithm for a reliable defect detection using an appropriate neural network.

Extension indices from digitalisation were then used in the SMCA analysis to evaluate PI. To assess the tunnel conditions, different categories of defects (i.e. masonry deterioration, water defects, seismicity, hydrology, superficial geology, and deep geology) have been considered. Table 2 lists the priority indices obtained for 14 sectors along the tunnel whose Extension index is in Figure 15.

The PI values highlight severe issues about the presence of water (more than 45 % for sectors 1, 12, 13,

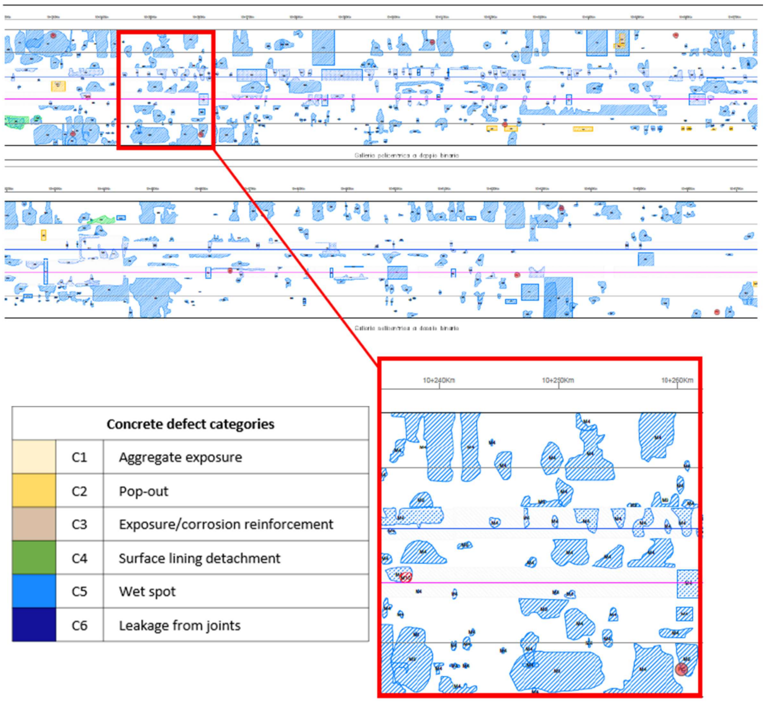


Figure 14. Example of a Defect Map.

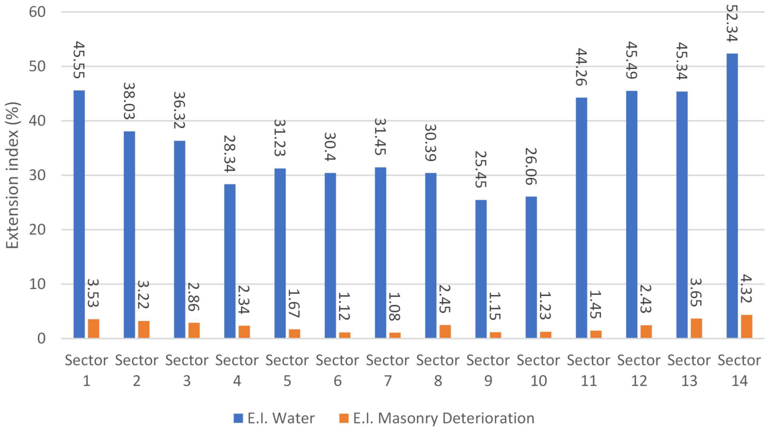


Figure 15. Extension Index: water and masonry distress.

Sector	Priority Index [%]	Masonry Deterioration [%]	Water [%]	Seism [%]	Superficial Geology [%]	Hydrology [%]	Deep Geology [%]
Sector 1	74.33	3.53	45.55	1.00	0.25	24.00	0.00
Sector 2	60.75	3.22	38.03	1.00	0.50	18.00	0.00
Sector 3	56.18	2.86	36.32	1.00	2.00	14.00	0.00
Sector 4	37.68	2.34	28.34	1.00	2.00	4.00	0.00
Sector 5	40.40	1.67	31.23	1.00	1.50	5.00	0.00
Sector 6	35.02	1.12	30.40	1.00	1.00	1.50	0.00
Sector 7	38.53	1.08	31.45	1.00	1.00	4.00	0.00
Sector 8	37.34	2.45	30.39	1.00	1.00	2.50	0.00
Sector 9	32.10	1.15	25.45	1.00	1.50	3.00	0.00
Sector 10	36.29	1.23	26.06	1.00	2.00	6.00	0.00
Sector 11	56.71	1.45	44.26	1.00	2.00	8.00	0.00
Sector 12	62.67	2.43	45.49	1.00	0.75	13.00	0.00
Sector 13	68.49	3.65	45.34	1.00	0.50	18.00	0.00
Sector 14	77.91	4.32	52.34	1.00	0.25	20.00	0.00

Table 2. Priority index over the tunnel sectors.

and 14) and hydrology (more than 15 % for sectors 1, 2, 13, and 14): the priority of intervention is barring hydraulic works and they will mainly concern water disposal. However, deep geology does not imply critical conditions for the surveyed sectors; seism (i.e., a constant value equal to 1 %) and superficial geology (the highest value is 2 % for sectors 4, 10, and 11) do not pose a threat.

4. Discussion

The MIRET framework is an organic approach for the efficient and effective maintenance of tunnels: it allows and objective and dynamic diagnostic, maintenance, and risk assessment to manage existing tunnels. The analysis of their conditions permits to determine the maintenance/rehabilitation procedures for restoring the defects identified by the equipment ARCHITA. Recent technologies allow the survey and inspection of tunnels and underground transport infrastructure with mobile mapping. These systems can run at different speeds, depending on the final precision and accuracy required by the activity goal of minimising interference to the traffic. The proposed multi-dimensional mobile mapping system has the advantage of speed, efficiency, safety, and reducing the time of work on the line. The ARCHITA equipment (e.g. thermal and linear cameras, laser scanners) gives a large set of outputs to be integrated and managed. The underground environment involves drawbacks of GPS signal loss and data calibration. Hence, alternative solutions can be adopted using cheap and available communication system infrastructure: wi-fi fingerprinting and QR calibration are currently used in most buildings for indoor positioning [35, 36]. Further analyses shall consider the influence of the placed technology, cables and other systems on the reliability of diagnostics of tunnel lining faults. This academic paper presents the methodology to manage data from GNSS+IMU sensors in tunnels and to map defects from high-resolution photos with manual and automatic procedures. The proposed approach stemmed from a study and has been implemented in two existing metro tunnels. On the whole, more than 40 km-long railway lines have been monitored to schedule their maintenance.

The presented methodology is versatile and can be implemented to study different tunnels, both railway and road ones. In particular, it could help to carry out digitisation, inspection, and diagnostics of underground transport systems to obtain a digital model of the work. The results contribute to the integrated platform to manage and identify critical conditions in existing tunnels. The reality-based information contributes by obtaining the as-built model of the tunnel to be used by the infrastructure manager during the facility service life. Indeed, the digital twin and its detected defects form a common data environment: the integration of the entire process in the BIM environment contributes to optimising the management process [37]. The potential of BIM allows different stakeholders to monitor the infrastructure conditions and schedule maintenance works, optimising resources, and minimise burdens [38]. The virtual reality inspection aims to verify the current state of the tunnel and gives objective geometric data and visual information to all parties. Indeed, monitoring allows a dynamic database and assessment of the structures to identify the best option from different perspectives. Moreover, the results from the proposed framework can be supplemented with the monitoring of technological equipment to ensure regular tunnel operation. Indeed, operational, economic, and environmental outputs highlight the need for a multidisciplinary study, to balance the often-conflicting objectives of tunnel managers, passengers, and citizens.

5. Conclusion

Transport infrastructures are large-scale works that require large investments and complex relationships between stakeholders. For this reason, it is necessary to manage them with a multidisciplinary approach. Multidimensional information should be considered to manage a facility during its service life to optimise geometric, operational, environmental, and economic variables that affect the scenario. Underground infrastructures are a major transport system that ensures public transport sustainability while balancing the often-conflicting objectives of their stakeholders. In general, today, all information regarding existing infrastructures is often fragmented and incongruent due to traditional methods of data collection and management. For this purpose, the presented process ARCHITA shall be integrated into the Management and Identification of the Risk for Existing Tunnels (MIRET) platform to process survey-inspection data. ARCHITA permits to collect geometrical and functional data using a laser scanner and linear and thermal cameras during the automatic survey and inspection activities. In the MIRET approach, the ARCHITA phases can be repeated to update data through different time steps. The multi-dimensional mobile mapping systems permit to collect information with non-destructive tests, preserving the integrity of the tunnel structures. The results give a solid base for preliminary technical assessments in the management of the tunnel structures and the whole infrastructure. Monitoring allows a dynamic database and assessment of the structures to identify the best option from different perspectives. The results allow a more objective and dynamic diagnostic, maintenance, and risk assessment to manage existing tunnels. Moreover, these analyses are a direct input for a later stage of planning, design, and construction. Within the MIRET framework, the authors are investing in the development of AI to manage multiscale resolution, extraction, aggregation, and reconstruction of surface damages on the tunnel concrete lining.

The results contribute to managing and identifying critical conditions, and scheduling maintenance work based on objective indices in existing tunnels. Further research should focus on the integration and recognition of defects and objects using an artificial intelligence.

References

[1] J. Rodrigue, C. Comtois, B. Slack. *The geography of transport systems.* Routledge, 2006.

[2] R. Schwartz, I. Gregory, T. Thévenin. Spatial history: Railways, uneven development, and population change in France and Great Britain, 1850-1914. *Journal of Interdisciplinary History* **42**(1):53–88, 2011. `https://doi.org/10.1162/JINH_a_00205`

[3] S. Jovanovic, A. Zoeteman. Modern condition-based railway infrastructure asset management. In *1st International Conference on Road and Rail Infrastructure*, pp. 801–808. 2010.

[4] E. Quatrini, F. Costantino, G. Di Gravio, R. Patriarca. Condition-based maintenance – an extensive literature review. *Machines* **8**(2):31, 2020. `https://doi.org/10.3390/machines8020031`

[5] M. Mili, F. Chille, C. Thuad. Comparison of international repair works practices in railway tunnels [In French; État de l'art des travaux de réparation en tunnels ferroviaires exploités en Europe]. In *16th International Congress AFTES 2021.* 2021. #117, `https://livebyglevents.key4register.com/key4register/AbstractList.aspx?e=30&preview=1&aig=-1&ai=4876`.

[6] P. Di Mascio, G. Loprencipe, L. Moretti. Competition in rail transport: Methodology to evaluate economic impact of new trains on track. In *3rd International Conference on Transportation Infrastructure, ICTI 2014 – Sustainability, Eco-Efficiency and Conservation in Transportation Infrastructure Asset Management*, pp. 669–675. 2014.

[7] J. Richards. Inspection, maintenance and repair of tunnels: International lessons and practice. *Tunnelling and Underground Space Technology* **13**(4):369–375, 1998. `https://doi.org/10.1016/S0886-7798(98)00079-0`

[8] T. Tichý, J. Brož, Z. Bělinová, R. Pirník. Analysis of predictive maintenance for tunnel systems. *Sustainability* **13**(7):3977, 2021. `https://doi.org/10.3390/su13073977`

[9] S. Biancardo, M. Intignano, N. Viscione, et al. Procedural modeling-based BIM approach for railway design. *Journal of Advanced Transportation* **2021**(17):8839362, 2021. `https://doi.org/10.1155/2021/8839362`

[10] A. Badshah, S. Ullah, D. Shahzad. Vision based tunnel inspection using non-rigid registration. In *Twelfth International Conference on Quality Control by Artificial Vision 2015*, vol. 9534, p. 95340J. 2015. `https://doi.org/10.1117/12.2182932`

[11] L. Attard, C. J. Debono, G. Valentino, M. Di Castro. Vision-based change detection for inspection of tunnel liners. *Automation in Construction* **91**:142–154, 2018. `https://doi.org/10.1016/j.autcon.2018.03.020`

[12] G. Loprencipe, L. Moretti, T. Pestillo, R. Ferraro. Railway freight transport and logistics: Methods for relief, algorithms for verification and proposals for the adjustment of tunnel inner surfaces. *Sustainability* **10**(9):3145, 2018. `https://doi.org/10.3390/su10093145`

[13] P. Zoccali, G. Loprencipe, R. C. Lupascu. Acceleration measurements inside vehicles: Passengers' comfort mapping on railways. *Measurement* **129**:489–498, 2018. `https://doi.org/10.1016/j.measurement.2018.07.079`

[14] J. C. Cheng, Q. Lu, Y. Deng. Analytical review and evaluation of civil information modeling. *Automation in Construction* **67**:31–47, 2016. `https://doi.org/10.1016/j.autcon.2016.02.006`

[15] A. Justo, M. Soilán, A. Sánchez-Rodríguez, B. Riveiro. Scan-to-BIM for the infrastructure domain: Generation of IFC-compliant models of road infrastructure assets and semantics using 3D point cloud data. *Automation in Construction* **127**:103703, 2021. `https://doi.org/10.1016/j.autcon.2021.103703`

[16] Y. Ghassoun, M. Gerke, Y. Khedar, et al. Implementation and validation of a high accuracy UAV-photogrammetry based rail track inspection system. *Remote Sensing* **13**(3):384, 2021. `https://doi.org/10.3390/rs13030384`

[17] A. Thaduri, D. Galar, U. Kumar. Railway assets: A potential domain for big data analytics. *Procedia Computer Science* **53**:457–467, 2015. `https://doi.org/10.1016/j.procs.2015.07.323`

[18] N. Davari, B. Veloso, G. Assis Costa, et al. A survey on data-driven predictive maintenance for the railway industry. *Sensors* **21**(17):5739, 2021. `https://doi.org/10.3390/s21175739`

[19] Y. Cheng, W. Qiu, D. Duan. Automatic creation of as-is building information model from single-track railway tunnel point clouds. *Automation in Construction* **106**:102911, 2019. `https://doi.org/10.1016/j.autcon.2019.102911`

[20] M. Bensalah, A. Elouadi, H. Mharzi. Overview: The opportunity of BIM in railway. *Smart and Sustainable Built Environment* **8**(2):103–116, 2019. `https://doi.org/10.1108/SASBE-11-2017-0060`

[21] F. Foria, R. Ferraro, E. Peticchia, et al. Modélisation des défauts et maintenance des tunnels existants avec une approche novatrice (MIRET): L'étude de cas de la ligne de chemin de fer gênes – vintimille et du métro de rome. In *26th International Congress AFTES 2021*, pp. 1–10. 2021.

[22] F. Foria, G. Avancini, R. Ferraro, et al. ARCHITA: An innovative multidimensional mobile mapping system for tunnels and infrastructures. *MATEC Web of Conferences* **295**:01005, 2019. `https://doi.org/10.1051/matecconf/201929501005`

[23] D. Aggelis, E. Kordatos, M. Strantza, et al. NDT approach for characterization of subsurface cracks in concrete. *Construction and Building Materials* **25**(7):3089–3097, 2011. `https://doi.org/10.1016/j.conbuildmat.2010.12.045`

[24] G. Sirca Jr., H. Adeli. Infrared thermography for detecting defects in concrete structures. *Journal of Civil Engineering and Management* **24**(7):508–515, 2018. `https://doi.org/10.3846/jcem.2018.6186`

[25] Software infinity, 2022. [2022-07-21], `https://leica-geosystems.com/en-gb/products/gnss-systems/software/leica-infinity`.

[26] Y. Ren, J. Huang, Z. Hong, et al. Image-based concrete crack detection in tunnels using deep fully convolutional networks. *Construction and Building Materials* **234**:117367, 2020. `https://doi.org/10.1016/j.conbuildmat.2019.117367`

[27] Python, 2022. [2022-07-21], `https://www.python.org/`.

[28] K. Nielsen. *Software Development with C++*. Elsevier, 1994. `https://doi.org/10.1016/C2013-0-11240-8`

[29] Tensorflow, 2022. [2022-07-21], `https://www.tensorflow.org/`.

[30] F. Foria, G. Miceli, A. Tamburini, et al. Application of spatial multi-criteria analysis (SMCA) to assess rockfall hazard and plan mitigation strategies along long infrastructures. *IOP Conference Series: Earth and Environmental Science* **833**:012074, 2021. `https://doi.org/10.1088/1755-1315/833/1/012074`

[31] 3DReshaper accueil | 3DReshaper available, 2022. [2022-07-09], `https://www.3dreshaper.com/fr/`.

[32] Software Trimble GEDO Office, 2022. [2022-07-21], `https://www.trimble-italia.com/prodotti/software/trimble-gedo-office`.

[33] L. Wright, S. Davidson. How to tell the difference between a model and a digital twin. *Advanced Modeling and Simulation in Engineering Sciences* **7**:13, 2020. `https://doi.org/10.1186/s40323-020-00147-4`

[34] Solibri, 2022. [2022-07-09], `https://www.harpaceas.it/solibri`.

[35] Z. Li, J. Huang. Study on the use of Q-R codes as landmarks for indoor positioning: Preliminary results. In *2018 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, pp. 1270–1276. 2018. `https://doi.org/10.1109/PLANS.2018.8373516`

[36] H. Gang, J. Pyun. A smartphone indoor positioning system using hybrid localization technology. *Energies* **12**(19):3702, 2019. `https://doi.org/10.3390/en12193702`

[37] G. Cantisani, J. D. C. Panesso, G. Del Serrone, et al. Re-design of a road node with 7D BIM: Geometrical, environmental and microsimulation approaches to implement a benefit-cost analysis between alternatives. *Automation in Construction* **135**:104133, 2022. `https://doi.org/10.1016/j.autcon.2022.104133`

[38] M. Leone, A. D'Andrea, G. Loprencipe, et al. Building information modeling (BIM): Prospects for the development of railway infrastructure industry. In *Proceedings of AIIT International Congress TIS Rome 2017*, pp. 547–553. 2017. `https://doi.org/10.1201/9781315281896-72`