Comprehensive Railway Track Monitoring Using Unmanned Aerial Systems (UASs) and Building Information Modeling (BIM)

Marinella Giunta(✉), Vincenzo Barrile, Giovanni Leonardi, and Emanuela Genovese

University Mediterranea of Reggio Calabria, 89124 Reggio Calabria, Italy
{marinella.giunta,vincenzo.barrile,giovanni.leonardi,
emanuela.genovese}@unirc.it

Abstract. The increasing adoption of UAV-based inspections in railway infrastructures stems from the demand for more efficient, cost-effective, and safer alternatives to conventional track monitoring practices, which typically rely on manual inspections or dedicated rail vehicles. UAVs offer the possibility to capture high-resolution images and detailed data from multiple perspectives, which can then be analyzed using cutting-edge computer software. In this way, a comprehensive assessment of various track components, such as rails, sleepers, fastening systems, and ballast, can be done. Additionally, combining drones with technologies like Building Information Modeling (BIM) allows for the development of precise digital representations of railway infrastructure. This research reports the results of the monitoring of the state of the track based on the images captured by a drone equipped with a video camera and the point cloud created by means of appropriate advanced software that uses photogrammetric techniques to transform a series of images into 3D spatial data. Advantages and limitations of UAVs for monitoring railway track conditions are highlighted as well as the optimization needed for reaching the precision suitable for the assessments. Results demonstrated the appropriateness of using the drone for monitoring and assessing track conditions, in terms of geometric and structural integrity, as well as maintenance requirements.

Keywords: Rail track · Preventive maintenance · Monitoring · Imaging · UAS

1 Introduction

Railways are an integral part of both passenger transport and freight logistics, becoming more and more crucial for the effective and sustainable movement of people and goods over short, medium and long distances. With the growth of traffic, axle load and speed in the railway network, the preservation of the infrastructure in terms of safety, integrity and overall functionality is an undiscussed priority [1, 2].

This requires diligent maintenance activities of the railway tracks, which are exposed to a lot of wear and tear in use, adequately supported by monitoring of their conditions [3]. Railway operators face several challenges in monitoring. Conventional track monitoring

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15894, pp. 407–419, 2026.
https://doi.org/10.1007/978-3-031-97648-3_27

practices, which typically rely on manual inspections or dedicated rail vehicles, have supported the railway industry for many years. However, due to the increased need for maintenance and optimization of resources and time the demand for more efficient, cost-effective, and safer alternatives has become increasingly pressing [4, 5].

The adoption of new technologies such as unmanned aerial vehicles (UAVs) and image elaboration is changing the way track monitoring is performed [6]. The UAVs application in track monitoring demonstrated that the advantages of their use include reduced time for inspection, reduced risk for operators, large areas covered quickly, a wide dataset acquired, reliability and simplicity, and digital reconstruction of assets.

UAVs can be used to inspect railroad components such as bridges [7, 8], tunnels [9], vegetation [10], and track conditions [11–14].

As regards the defect of rail superstructure, the horizontal, vertical or composite track irregularities can greatly affect the safety and the comfort of passengers.

Ravitharan [12] proposed a novel approach for monitoring various aspects of track geometry by means UAVs, with a particular focus on rail vertical alignment, twist, curvature, and running surface issues, including discrete defects and rail corrugation.

Qui [13] developed a UAV-LiDAR-based platform capable of performing track geometry measurements. It demonstrated high accuracy in gauge measurement, although its performance in curvature and profile measurement was less effective.

Wu [14] explored the use of UAVs for track gauge measurement. They generate a point cloud of the railway scene and apply a hybrid segmentation algorithm combining augmented region-growing and improved alpha-shape techniques to extract rails from chaotic data. Rails features are compared with a pre-built rail BIM model. The validation of the proposed method demonstrated its superiority in safety, efficiency, speed, and accuracy.

The high-resolution images and detailed data from multiple perspectives, captured by drones, can be analyzed using cutting-edge computer software. In this way, a comprehensive assessment of various track components, such as rails, sleepers, fastening systems, and ballast, can be done. Additionally, combining drones with technologies like Building Information Modeling (BIM) allows for the development of precise digital representations of railway infrastructure [15, 16].

This paper proposes in Sect. 2 a methodology for monitoring track conditions using images captured by a drone equipped with a camera, which are then used to reconstruct a digital representation of the track within a BIM environment. The methodology is applied to a case study referring to a 1 km-long railway line section, flown over with the drone. Using advanced software utilizing photogrammetric techniques, the series of images captured with the drone was transformed into 3D spatial data, as reported in Sect. 3. Section 4 discusses the results of the application and highlights both the advantages and limitations of using UAVs for monitoring railway track conditions, as well as the optimization needed to achieve the precision required for accurate assessments.

2 Methodology for Monitoring Railway Track Conditions

This research focuses mainly on the potential of using drones to monitor a railway infrastructure by emphasizing the pros and cons of this technology in accurately identifying damages, subsidence or other deterioration conditions affecting the railway section.

The methodology proposed for this purpose and applied to 1-km of existing track railway section is divided into three phases: the *data collection*, involving the planning and execution of the drone survey, the *data elaboration*, were the acquired imaged are processed by means of advanced software, and the *results evaluation*, in which in which the rail track is modeled to enable geometric and structural assessments.

Figure 1 reports the flowchart of the proposed methodology described in more detail below.

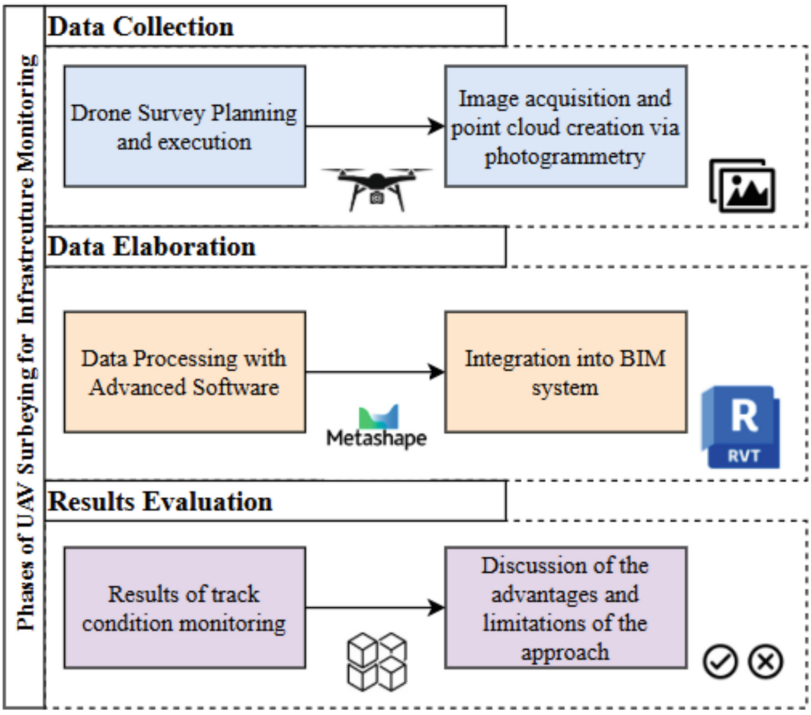


Fig. 1. Flowchart of the proposed methodology for monitoring of the state of the track based on the images captured by drone.

The first phase involved the data acquisition necessary for the analysis to be carried out in the following phases. For the case study under investigation, the survey was conducted using a DJI Mavic 3 Enterprise drone, equipped with a high-resolution quadrangular CMOS 4/3 camera, offering 20 effective megapixels, a field of view (FOV) of 84°, and an aperture of f/2.8 to f/11. This family of drones is well-known for its agility, relatively low cost, and high-precision results thanks for its specific configuration.

The acquisition of the drone's images was carried out based on a detailed flight plan, properly designed and optimized for this specific case study to ensure a level of detail and precision required for the planned experimentation.

To this end, the Pix4D application was used, which allowed setting flight parameters including flight altitude, Ground Sampling Distance (GSD), number of captured frames,

longitudinal and transverse overlap, as well as path and speed that the drone must follow and maintain during automated flight. This phase is crucial for obtaining a high-quality and correctly georeferenced 3D model.

In this specific case, an inspection and a planimetric framing of the area were carried out, to then establish the flight parameters. The drone flew at an altitude of 69.5 m along a grid path, the GSD was set to 1.82 cm/pixel. A total of 177 nadir images were captured with an overlap of 80% in both directions (see Table 1). Additionally, a separate flight was conducted without programming to take oblique images to better capture the characteristics of the railway.

Table 1. Parameters of flight.

Parameters	Value
Height of flight	70 m
Speed of flight	12 km/h
Covered Area	0.103 km^2
GSD	1.82 cm/pixel
Front overlap	80%
Side overlap	80%
Number of Nadir images	177

The acquired images have a resolution of 4864 x 3648 (camera model). The calculated error in the camera positioning resulted in average errors of X = 5.45 mm, Y = 3.38 mm, and Z = 6.32 mm (see Fig. 2).

Figure 2 shows the error ellipses, a concept commonly used in geodesy and cartography to represent the uncertainty zone of geospatial data. The black dots in the figure indicate the position measurement, while the ellipse represents the probability distribution, highlighting the area where the true position is likely located.

In this case, the ellipse represents the uncertainty in georeferencing of the images. The shape of the ellipse provides information in the X and Y directions, while the color indicates the error in the Z axis. From this, we can estimate an overall mean uncertainty in the georeferencing of the images of approximately 9.00 mm.

Once the data collection phase was completed, images were processed in the Agisoft Metashape environment, which employs Structure from Motion algorithms for the photogrammetric process and the subsequent creation of 3D models. During this second phase, the images were imported into the Agisoft Metashape and aligned. The alignment of the images is the process in which characteristic points are identified and paired in order to create the sparse point cloud.

This process permits the matching of images with a pairwise comparison. For the image alignment, the generic preselection and reference preselection options were used, which rely on selecting the camera positions at the time of image capture. In this case, the images that were closest to each other and had the highest probability of sharing more characteristic points were selected. Having geotagged images available, the source of the

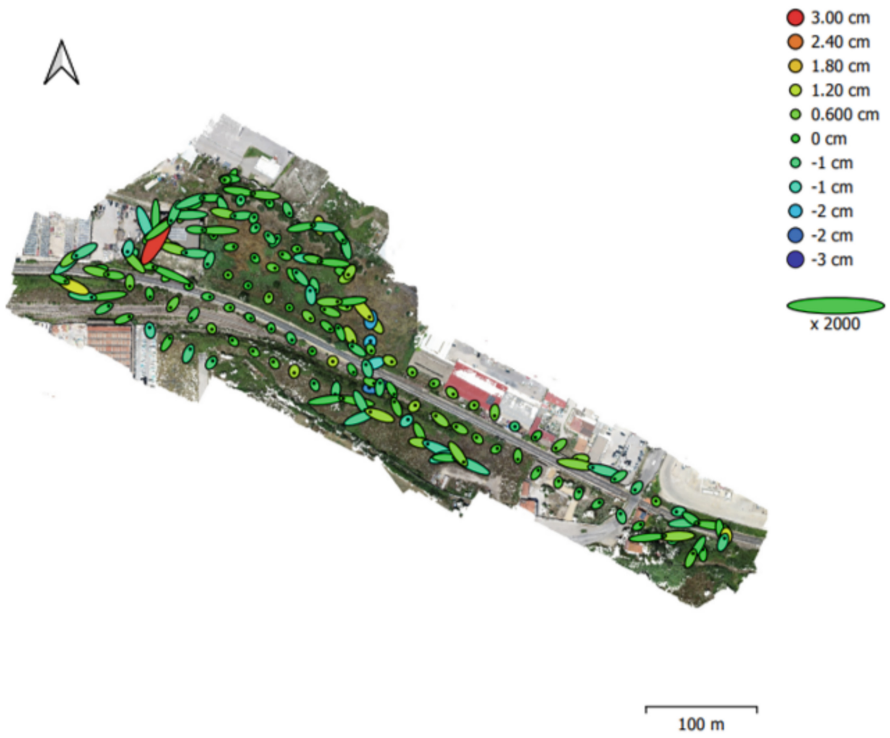


Fig. 2. Average camera position error.

images was used to calculate the position of the cameras. The end was to give the software the possibility to optimize its process without losing a large amount of information. In fact, the generic preselection reduces the processing and image alignment time. The reference preselection is equally important, as it ensured that images without stable common points were discarded. For the image alignment, high accuracy was chosen, ensuring that the initial resolution of the images was maintained.

After generating the sparse point cloud, scaling and orienting it, according to the aforementioned details, and correcting any distortions, the dense cloud was generated. The dense point cloud provided a high density of information on the ground and on the above elements, which are the focus of the three-dimensional reconstruction. To achieve this, the "high-quality" option was used for generating the point cloud, which affects the resolution of the images considered when identifying points that will become part of the dense cloud (see Fig. 3).

In a Structure from Motion process, the support points (Ground Control Points) alone are not sufficient to determine the accuracy of the point cloud and the subsequent three-dimensional model. In fact, in addition to the support points used to optimize the point cloud and therefore to deform, scale, move, and orient it, it was necessary to have additional points, called check points, measured using GNSS instruments. The check points enable to perform a statistical analysis on the deviations to determine the average error. The average error was calculated by analyzing the root mean square deviations



Fig. 3. Dense Point Cloud generated in Agisoft Metashape environment.

between the X, Y, Z coordinates assigned by the software to the points of the generated sparse cloud and the corresponding coordinates of the check points. The resulting average error across the three coordinates was approximately 2 cm.

The proposed method also includes a series of intermediate steps between the various main phases, which are essential for obtaining the desired results.

The first phase, as previously mentioned, involves programming the flight plan.

In this case, the plan was optimized to ensure the best possible performance in terms of both processing efficiency and the quality and accuracy of the resulting point cloud. During the planned flight, the drone captured a series of frames, which were stored on an external SD card for later transferred to a PC dedicated to processing. In addition to the acquired images, 20 points were surveyed using GNSS equipment, of which 5 served as check points to verify the accuracy of the generated point cloud. Once the process of optimizing the cameras, aligning and importing the GCPs into the sparse cloud for orientation, movement and scaling of the sparse cloud had started, the accuracy of the cloud was assessed using check points.

At the end of these steps, the mesh and texture were generated, moving from a discontinuous point-based visualization to a continuous surface representation. The points of the dense cloud became the vertices of the triangles of a network that constitute the surface inheriting the color information associated with those vertices. Using the same dense point cloud obtained from the photogrammetric processing and the resulting 3D model, the Building Information Model (BIM) of the railway track was then created.

As is known, BIM is a methodology widely used today used in the construction sector for the design and construction of buildings. It allows for the integration of dimensions, materials, and other important technical specifications in the modeling phase. The process to create the BIM model can take place either directly from the point cloud or from the 3D model, producing a real three-dimensional BIM model.

In order to use the model within the software, it was first necessary to export the model in a format compatible with BIM software, i.e., .obj or. fbx, using Autodesk Recap software. This software permits the management, decimation, and merging of clouds not only derived from photogrammetric processes but also from terrestrial laser scanners acquisitions (see Fig. 4).



Fig. 4. Dense Point Cloud from Autodesk Recap environment.

Subsequently, Autodesk Revit software was used for the BIM modeling phase, starting from the generated 3D model and enriching it with specific details such as materials, accurate geometries of the elements, and some structural details. The various components of the railway section were modeled, starting from the terrain, through the "topographic solid" function. For the other components, custom families representing the components of the railway section were defined. In particular, the generated 3D model served as a reference to precisely place BIM objects corresponding to railway components, such as sleepers, tracks, ballast layer, and other features. To this end, the concrete sleepers were inserted, along with the precise geometry and type of attachment, once the steel rails were modeled. The ballast, which plays a crucial role in ensuring the durability and stability of the track, was added at the base of the railway layout. This modeling process enables the identification and assessment of potential defects in the analyzed section of the railway.

It should be noted that manual surveys for infrastructure monitoring require experienced and qualified personnel on site, equipped with total stations and differential GPS to perform precision measurements. These surveys are time-consuming, often requiring several days or even weeks, also due to the interference with rail traffic, as train circulation must be interrupted or slowed down on the day of the survey. Moreover, the data collected refer only to the specific survey and provide solely 2D documentation, which is subject to interpretation errors.

Unlike these methods, the proposed method allows for rapid and automated surveys, reducing the time and costs while covering larger areas in less time. Apart from specific authorizations, altitude limits, and obstacle control in the surveyed area, this type of survey does not interfere with railway operations in any way, making it possible to perform frequent updates and generate a 3D and BIM model that supports structural simulations, analyses, and advanced redevelopment planning. The main drawback lies in the need for advanced skills in Geomatics, particularly in topographic surveys and 3D modeling, as well as cross-disciplinary expertise for evaluating the necessary interventions.

3 Results of Track Condition Monitoring

3.1 3D Modeling

The results of the 3D modeling process, as extensively detailed in Sect. 2, carried out in the Agisoft Metashape environment, are shown in Fig. 5.

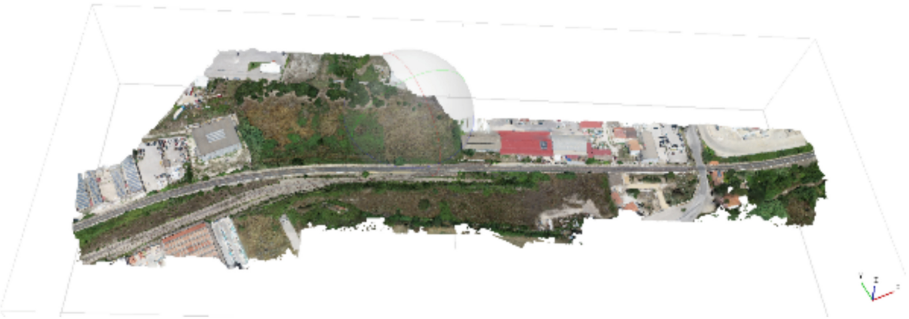


Fig. 5. 3D model textured generated in Agisoft Matashape environment.

The process was initiated on a workstation equipped with an Intel Core i7, 32 GB of RAM, and 1 TB of storage, featuring an integrated Intel graphics card. It took approximately 45 min to generate the dense point cloud. The processing time was correlated to the high number of points to be processed (116,712,923 points) and to the parameters set for generating the dense cloud and producing the 3D model. The careful selection of these parameters at this stage was crucial in drastically reducing the computational time.

From the 3D model produced, it was possible to conduct a detailed analysis of the geometry of the railway track, in order to verify compliance with regulations and identify any anomalies in portions of the track that could compromise its safety.

In particular, the 3D model enabled the evaluation of wear and tear on the rails and the state of the concrete sleepers, facilitating informed decisions on the maintenance of the railway section.

From the results obtained, it was possible to precisely measure the standard gauge, which for the entire section taken into consideration is equal to 1435 $\pm$ 2 mm, without detecting significant irregular variations (Fig. 6).

Cross-sections were also generated to verify the overhang of the outer rail in the curves; in this case, the railway section did not show significant differences in height between the rails.

Regarding the ballast, it was possible to detect some areas contaminated by vegetation, which could compromise its stability.

The analysis of the slope along the entire section, derived from the generation of the DSM (Digital Surface Model), was equally important, as it enables the visualization of the height fluctuations and slope changes along the stretch. The slope was calculated using a DSM created within Agisoft Metashape, which provides elevation data for the area under examination, including the heights of buildings, vegetation, and any objects



Fig. 6. Detail of the railway track and measurement of the distance between tracks.

above ground level. The software includes a workflow that allows the creation of the DSM starting from the dense cloud. Once the reference system (CRS: WGS84 UTM 33N) and the resolution of the DSM were defined, the DSM creation process was started. The slope analysis was then performed in the QGIS environment. The slopes were found to be within acceptable limits for the flat section, maintaining a gradient of 10‰.

Thanks to the analysis of the three-dimensional model, it was therefore possible to study the actual state of the area being analyzed, obtaining detailed geometry and a realistic texture of the infrastructure useful for topographic analysis of the railway section. In particular, the morphology of the route, the curvatures, the slopes, as well as the longitudinal and transversal profiles, were analyzed for altimetric and planimetric insights. Furthermore, automatic extraction methods of geometric features from the 3D model and automatic segmentation methodologies, based on the use of neural networks, useful for selecting various portions of the infrastructure, are being tested. The use of convolutional neural networks on point clouds, which classify directly without the need for meshing, allows for the automatic classification of rails, sleepers, and ballast. In this case, it would be necessary to optimize the parameters of networks such as PointNet and RandLA-Net to improve the accuracy of segmentation of high-resolution point clouds.

This type of inspection provides valuable insights for planning targeted maintenance activities, enabling more efficient scheduling and contributing to a reduction in both time and operational costs.

3.2 BIM Modeling

BIM is a relevant tool for the management and maintenance of the railway section by enabling the representation of the railway components through parametric elements containing detailed technical information on materials and dimensions, ensuring the possibility of carrying out simulations and planning interventions (Fig. 7).

The 3D model of the section represented in Fig. 7 has a Level Of Detail (LOD) of 300, which guarantees that the objects of the model can be accurately positioned within the

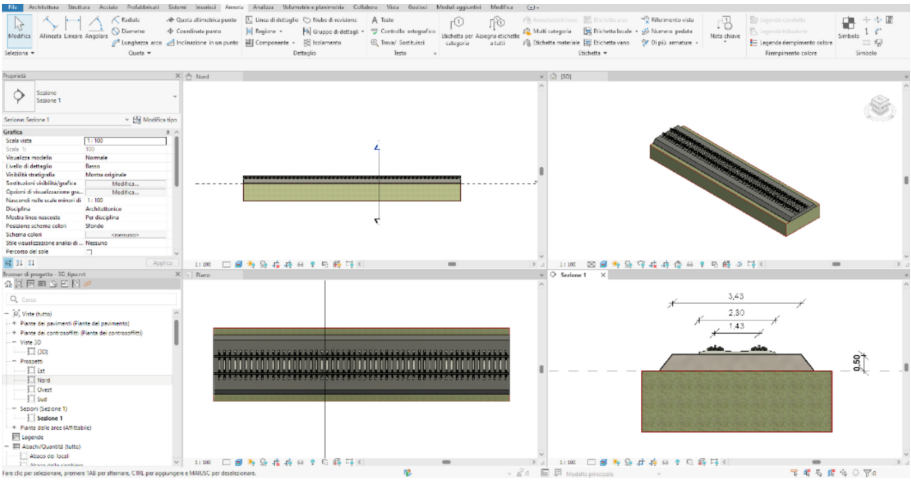


Fig. 7. Autodesk Revit: BIM of the railway track.

project and faithfully reproduce the dimensions, shape, position, and orientation of the represented object. As for the parameters evaluated, these refer to the distance between the rails, the thickness of the ballast, and the slope. There are specific tools within the Agisoft Metashape software that allow the accurate measurement of distances within the 3D model (always considering the average error of the restitution of 2 cm).

BIM modeling, based on the actual state of the railway section, provides important information for intelligent maintenance of the infrastructure, guaranteeing the possibility to simulate the work schedule through the analysis of construction times, the integration of economic data for cost control, and resource management.

In this specific case, the creation of the BIM model starting from the survey carried out with the drone permitted the recreation of the plano-altimetric feature of the railway section and provided useful information for future interventions. For example, the railway line under investigation is not yet electrified, and it could be subject to modernization and electrification interventions, using BIM to simulate the ideal positioning of poles and power cables.

Furthermore, BIM enables the management of information related to environmental sustainability and energy efficiency, supporting the selection of appropriate materials for designing and implementing low environmental impact interventions. Thanks to these capabilities, BIM allows for the management of the entire infrastructure lifecycle, including the monitoring and tracking of the wear condition of each component within the railway section.

4 Conclusions and Future Work

This research focused on the use of drones for constructing 3D and BIM models of a railway section, achieving a high level of precision and detail that enabled significant geometric analyses and demonstrated the potential of these technologies for detecting deterioration and subsidence within the infrastructure.

The advantages of drone-based surveys are well known they allow for the continuous generation of up-to-date 3D models of railway infrastructure, offering detailed, real-time information and enabling the identification of damage and deformations with centimeter-level accuracy. On the other hand, it should be noted that railway areas, especially in Italy, are not always accessible without the necessary permits and certifications, in addition to the specific license required for the drone operator. Additionally, drone surveys are influenced by weather conditions and limited flight autonomy, which tend to decrease in certain areas and conditions. Moreover, drones may not always be able to capture images from all the necessary angles for an accurate reconstruction, making precise and strategic flight planning essential.

The integration of BIM in railway projects offers significant advantages in all phases of the infrastructure's life cycle: in the design phase, BIM enhances the overall quality of the designed infrastructure, improving its performance in terms of safety, security, and resource management; in the construction phase, BIM is useful for optimizing the work scheduling, resource management, time, and costs; and during the operation phase, BIM improves maintenance processes and facilitates the integration of modifications throughout the infrastructure's lifespan.

Therefore, while the 3D model allows for accurate monitoring of the infrastructure's status, the BIM model enables advanced management throughout all phases of design and maintenance. Integrating the BIM design model with the monitoring model permits the identification of potential issues that may arise over time in the railway section, providing valuable insights for planning and optimizing maintenance interventions.

The strength of the proposed methodology lies mainly in the possibility of using rapid procedures and measures for monitoring the railway section. The practical limitations of the entire proposed process lie in the size of the images to be processed and, consequently, in the size of the point cloud at the base of both the 3D model and the creation of the BIM model. A further limitation consists of the need to process the images on a computer that can guarantee the best performance in terms of advanced graphics, in order not to have excessively high processing times. Furthermore, the process requires specific skills in the use of topographical instruments, photogrammetric processing software, and BIM. Regarding the costs of the proposed solution, it is necessary to take into account the initial costs related to the purchase of the equipment and the proprietary software used. The purchase of the drone requires insurance, while the GNSS equipment involves an additional cost for the subscription to the positioning satellites. Regarding the software, the licenses may vary. The cost of such equipment is, however, justified, considering that the monitoring of an entire railway section with traditional methods can end up having the same cost, but with the need for longer times to carry out the survey activities. Finally, the drone operator must acquire the necessary license to operate.

The proposed methodology also provides benefits to several stakeholders. For project managers and construction companies, the combined use of drones and BIM facilitates data collection and monitoring operations, significantly reducing the need for specialized labor. For engineers, this methodology ensures precision and accuracy, allowing for reliable and accurate measurements that are not subject to interpretation errors, also thanks to the possibility of using tools such as drones, equipped with very high-resolution cameras, which allow for more detailed and precise spatial data with minimal average

error. This methodology improves collaboration between designers, as the level of detail achieved allows for realistic and geolocalized representations of infrastructures and for a greater understanding of the interventions to be carried out.

Future work could involve the integration of additional geomatics and artificial intelligence techniques to improve advanced analyses on railway infrastructures. Drones equipped with multispectral sensors could be used to identify variations in humidity and ballast grain size, while georadar could be used as a tool to identify any subsidence areas in the section. Furthermore, artificial intelligence techniques could help in the automatic segmentation and classification processes of portions of the point cloud for subsequent BIM modeling. Future analyses could also focus on applying post-processing techniques to convolutional neural networks to further refine the results achieved by global segmentation, by applying morphological filtering algorithms.

Acknowledgments. This study was carried out within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. European Commission. Seventh monitoring report on the development of the rail market under Article 15(4) of Directive 2012/34/EU of the European Parliament and of the Council (2021)
2. Giunta, M.: Trends and challenges in railway sustainability: the state of the art regarding measures, strategies, and assessment tools. Sustainability **15**, 16632 (2023)
3. Sedghi, M., Kauppila, O., Bergquista, B., Vanhataloa, E., Kulahcia, M.: A taxonomy of railway track maintenance planning and scheduling: a review and research trends. Reliab. Eng. Syst. Saf. **215**, 107827 (2021)
4. Aela, P., Cai, J., Jing, G., Hung-Lin Chi, H.-L.: Vision-based monitoring of railway superstructure: a review. Constr. Build. Mater. **442**, 137385 (2024)
5. Guerrieri, M., Parla, G., Celauro, C.: Digital image analysis technique for measuring railway track defects and ballast gradation. Measurement **113**, 137–147 (2018)
6. Barrile, V., Fotia, A., Leonardi, G., Pucinotti, R.: Geomatics and soft computing techniques for infrastructural monitoring. Sustainability **12**(4), 1606 (2020)
7. Bolourian, N., Hammad, A.: LiDAR-equipped UAV path planning considering potential locations of defects for bridge inspection. Autom. Constr. **117**, 103250 (2020). https://doi.org/10.1016/j.autcon.2020.103250
8. Cabral, R., et al.: Railway bridge geometry assessment supported by cutting-edge reality capture technologies and 3D as-designed models. Infrastructures **8**(7), 114 (2023)
9. Zhang, R., Hao, G., Zhang, K., Li, Z.: Unmanned aerial vehicle navigation in underground structure inspection: A review. Geol. J. **58** (6) (2023) 2454–2472. ISSN: 0072–1050. https://doi.org/10.1002/gj.4763

10. Rahman, M.A., Mammeri, A.: Vegetation detection in UAV imagery for railway Monitoring, In: Proceedings of the 7th International Conference on Vehicle Technology and Intelligent Transport Systems - VEHITS, pp. 457–464 (2021) ISSN: 978–989–758–513–5. https://doi.org/10.5220/0010439904570464
11. Sherrock, E., Neubecker, K.: Unmanned aircraft system applications in international railroads, in, United States. Federal Railroad Administration. Technical Report DOT/FRA/ORD-18/04 (2018)
12. Ravitharan, R., Chevin, J., Chung, H., C. Vong, Zhang, D.: The Implementation of Unmanned Autonomous Systems for Railway Inspection. In: Proceedings of the International Heavy Haul Association (IHHA), 10–14 June 2019, Narvik, Norway
13. Qiu, L.: Development of UAV-based rail track geometry irregularity monitoring and measuring platform empowered by artificial intelligence, UNLV Theses (2022). https://doi.org/10.34917/31813346 from
14. Wu, J., Limei Peng, L., Sheng, W., Changxin Wang, C., Sun, J.: Track gauge measurement based on model matching using UAV image. Autom. Constr. **155**, 105070 (2023)
15. Sahebdivani, S., Arefi, H., Maboudi, M.: Rail track detection and projection-based 3D modeling from UAV point cloud. Sensors **20**, 5220 (2020)
16. Barrile, V., Genovese, E., Favasuli, F.: Development and application of an integrated BIM-GIS system for the energy management of buildings. WSEAS Trans. Power Syst **18**, 232–240 (2023)