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A possible implementation of non-destructive data surveys in the definition of BIM models for the analysis of road assets

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Abstract

Recently, a strong push towards the use of BIM-based procedures and practices in the field of linear transport infrastructures has been addressed. In Italy, a series of ministerial decrees have been approved to encourage the use of this methodology in the design and management operations of civil works. In such a framework, a novel approach to the management phases of civil works is required, based on different types of data and analyses within an integrated process, making use of digital models of the assets. This study aims at defining a procedure able to integrate non-destructive surveys data, such as those from Ground Penetrating Radar (GPR) and Mobile Laser Scanner (MLS), into a BIM model of a road infrastructure. The different types of surveys allow to implement useful and multiple pieces of information regarding the assets of the infrastructure in the corresponding BIM model. The main goal of the research is to optimize the management phase of a road by combining different observations, made by separate operators, in a unified BIM environment, to define a methodology that can be applied to real infrastructures. In order to validate the proposed methodology, a digital model of a real highway has been generated by making use of non-destructive survey data obtained from inspections that have been carried out by means of GPR and MLS. The different datasets have been individually processed so that they could be unified in a single BIM model. As a result, the use of specifically designed parametric sections, along with the processed datasets, allowed to define a BIM model of the road that can also be analyzed in areas that usually cannot be reached by operators. This allows a more efficient management of the asset, showing that the proposed methodology could be a viable tool in the monitoring operations of linear transport infrastructures.

Keywords: Infrastructures Building Information Modeling (i-BIM); Ground Penetrating Radar (GPR); Mobile Laser Scanner (MLS); Non-Destructive Technology (NDT); Transport infrastructures.

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1. Introduction and literature review

The growth of Building Information Modeling (BIM) in civil engineering applications is driven by a European political impulse to increase the construction and management industry's efficiency (Aaron C. et al., 2018). The European Union Public Procurement Directive (EUPPD) (EU, 2014) mentioned that the European Member States may encourage, specify or mandate the use of BIM for publicly funded construction and building projects by 2016. Accordingly, the Ministry of Infrastructure and Sustainable Mobility (MIMS) in Italy has decreed BIM-based procedures for contractors to be gradually integrated into major public tenders (MIT, 2017). Another important document was recently issued, which partially updates and unifies the previous ones, with the main goal of increasing efficiency and effectiveness across the entire public works sector, with a specific focus on transport infrastructures (MIT, 2021). Furthermore, following the collapse of the "Morandi bridge" occurred in August 2018 in Genoa, new decrees were issued focused on the improvement and evaluation of the safety and resilience of the national transportation infrastructure network, as well as risk categorization and management, safety assessment, and bridge monitoring (MIT, 2018; CSLP, 2019). More specifically, these directives specify that the adoption of BIM-based methods for the management of existing civil infrastructures should be implemented, even if nowadays it is only required at an experimental level.

Within this context, the implementation of continuous and efficient road management procedures is essential to maintain the highest required functional and safety requirements, ensuring the safety of users and the community. Among them, Non-Destructive Testing methods (NDT) such as Mobile Laser Scanner (MLS), satellite-based technologies (e.g. InSAR) and Ground-Penetrating Radar (GPR) have been successfully applied to achieve extensive and efficient assessments without compromising the road's structural integrity (D'Amico et al.,2021, Gagliardi et al., 2021 a,b,c,d, Tosti et al., 2021). In particular, several studies established the usefulness of the monitoring application to bridges and roadways using both the GPR and the MLS to evaluate the quality of the pavement of roadway infrastructure (Tosti et al., 2020; Bianchini Ciampoli et al., 2020; D'Amico et al., 2020) and accurately describe the geometry of the civil element with millimeter precision (Brazzetti et al., 2016; Ham and Lee, 2018; Znobishchev and Shamraeva, 2019; Barrile et al., 2020).

Following to the NDT surveys, an optimized management program may be evaluated to optimize the analysis and the storage of the often remarkable amount of data with different temporal and spatial resolutions. A key part of these procedures is related to the selection and storage of relevant information with the main aim of improving the efficiency in the planning and execution of future interventions. In view of the above, the implementation of BIM models appears to be among the best solution (Panah, Reihane and Kioumarsi, 2021; Maltinti et al., 2021) allowing for a more effective administration of the transportation assets (D'Amico et al., 2022).

This study intends to define a viable technique for incorporating non-destructive survey data into BIM models for the analysis of road assets, with the main goal of guaranteeing a more effective storage, evaluation and interpretation of the data from on-site inspections. Furthermore, since the BIM models can be progressively updated at each new survey, they can be used to monitor potential changes in the infrastructure health conditions. This allows the detection of pavement and other road components distresses, as well as the control of their evolution over time, while being aware of the impact of any maintenance delays.

2. Data input from Non-Destructive Testing surveys

The ability to incorporate information into digital models is a crucial component of the BIM approach. These models must store data and the required information implemented for the evaluation of the condition and the internal state of the inspected infrastructure. As a result, the development of their various components is aimed at automating the digitalization process and the creation of a BIM model receiving the input data collected by several NDTs surveys. As a first step, survey data must be managed to provide the essential information to build the digital model. The implementation of parametric elements, which can adapt their properties to the information directly detectable by on-site surveys, allows for the integration of infrastructure data. Finally, the digital model is produced using these parametric components, as well as the modified data retrieved from the surveys. The study's findings are part of a greater road management procedure, which can be accomplished by regularly updating the model using the same methods as described above, after each round of surveys, or maintenance activities on the infrastructures, are completed. The objective is to present a novel methodology able to use the results obtained from a series of on-site NDTs surveys, thereby proposing a new way of exploiting and managing the available data that integrates them into a unique digital model associated to the investigated infrastructure. This procedure paves the way for the implementation of a Digital Twin Model of the inspected infrastructure, which can be progressively updated with new information every time that a new survey is conducted.

In particular, the main aim is to analyze the validity of the current high-performance survey techniques and to evaluate possible optimizations of the survey process for a more comprehensive modeling for the application of BIM methodology in the phases of management and monitoring of existing civil works. To this intent, a novel process is proposed allowing the management of data obtained from non-destructive surveys on a transport infrastructure and subsequently developing a phase of "data integration" in which different categories of data can be integrated into a single digital information model. Taking a step forward in the state-of-the-art research, a specific goal is to feed processes for the integration of data from high-performance surveys.

In more detail, the proposed methodology integrates different datasets generated by non-destructive investigations (i.e. MLS and GPR surveys) carried out on a linear transport infrastructure into a BIM model, thereby generating a complete digital model including also the structural elements of elevated structures. The point clouds obtained from the laser scanner also enable the geometric definition of the model and its location in a georeferenced system.

2.1. Survey instruments

The starting point for the development of a maintenance management system consists in the survey of the functional and structural characteristics of the infrastructure. Non-destructive surveys of road infrastructures and structural elements of structures require several examinations, tests and surveys which require different resolutions and technologies of investigation, aimed at ascertaining the conditions required to guarantee the safety of the infrastructure under examination.

There are different possibilities to conduct a laser scanner survey, which are strictly related to the required work purposes. The instrument used during the inspection presented in this paper is a Mobile Laser Scanner (MLS) which was mounted onto an instrumented vehicle to inspect several kilometers of a real infrastructure while maintaining a substantial speed. In addition, a Terrestrial Laser Scanner (TLS) was employed as well to obtain a greater accuracy associated to the georeferencing phase and a comprehensive reconstruction of the structural elements that are not visible from the road surface (e.g., bridge piers or abutments).

Moreover, the road stretch was tested by GPR. In particular, the GPR was equipped with an air-launched horn antenna having a central frequency of 1000 MHz. The acquisition system was mounted onto a survey vehicle through a support including a suspended beam that allowed the antenna to work at the correct height from the pavement surface.

The data obtained from these surveys were used to support the digitalization process of the infrastructure, starting from the measurements obtained from the point cloud increasing the level of detail through the information collected by the GPR technology.

3. Data integration and digital modeling

After the collection of the non-destructive data, it is then possible to start the data integration process, as the main objective is to create a digital model of the infrastructure, capable of storing all the information detected through on-site investigations by different technologies. The first stage of the proposed workflow includes the management of the data collected on-site, extracting the information needed to proceed in the phase of digital modeling. The following stages complete the process of data integration, by creating a digital model of the inspected infrastructure, including several components, such as the pavement and the barriers, as well as the main elevated structures (i.e., viaducts and bridges). The workflow hereby presented is shown in Fig. 1.

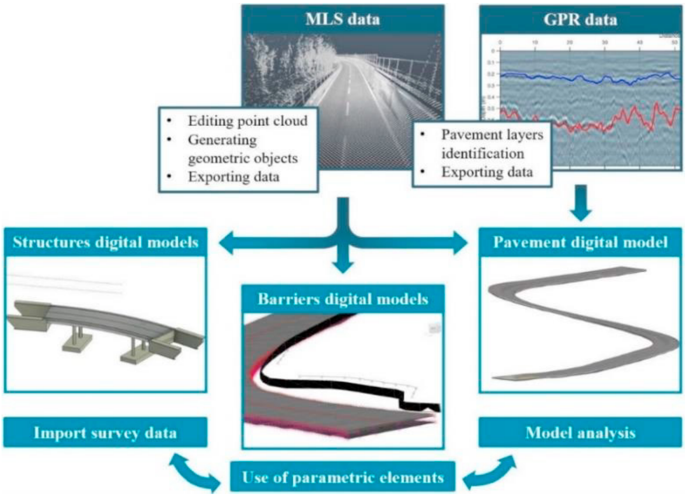

Fig. 1. workflow for the implementation of survey data in the definition of BIM models.

3.1. GPR data management

The GPR datasets were processed using the most recommended approaches found in literature, to extract valuable information on the pavement structure, including information of the layer thickness and the presence of voids and cracks (Loizos and Plati, 2007; Bianchini Ciampoli et al., 2019). The layering configuration of the pavement is a critical information in the implementation of the proposed methodology. Resurfacing treatments, inadequate dielectric contrast across layers (e.g., base to subbase), and incorrect survey design (e.g., central frequency of application) are all issues that may prevent clear layer detection, highly affecting the results and the reliability of the BIM model. The collection of several information on both pavement design and recent maintenance operations, as well as the extraction of corings along the surveyed stretch, are always recommended to reduce, and in some cases remove, any potential errors associated to the misinterpretation of the data and, as a result, a faulty reconstruction of the pavement layout. Starting from the receiving time of the reflections in the processed data, GPR scans were made by analyzing the speed of the electromagnetic signal as it passes through the material that forms the road's superstructure. In these scans the intensity of the signal is shown in relation to the depth of the pavement and the length of the GPR trace, by means of a chromatic scale. From these elements it was possible to recognize the configuration of the pavement layers. It is worthy of note that the inclusion of GPR data into BIM and Digital Twins models is not generally implemented, especially for network-scale surveys, due to several difficulties associated to the creation of the model starting from the B-scans detected by electromagnetic inspections. To overcome these limitations a novel procedure was implemented, aimed at creating polylines directly associated to the layers detectable by GPR outputs. To create these elements, a series of points were obtained by managing the GPR database which was georeferenced by simultaneous GPS acquisitions. These points are described by the coordinates x and y referring to their latitude and longitude respectively, while z referring to the depth of the layers' interface. By linking those points, a pair of three-dimensional polylines were constructed for each GPR trace, referring to two layers of pavement modeled in this study. In particular, the interface between the Hot-Mixed Asphalt (HMA) and the base course, as well as the interface between the subbase and the subgrade, were analyzed and modeled into a BIM platform. Furthermore, the polylines created in the previous phases, were used in the consecutive stages of the process as targets for the parametric objects that make up the digital models.

3.2. Laser Scanner data management

The initial stage of the procedure associated to the management of the Laser Scanner data was based on the creation of the point clouds generated by the MLS in order to make it more manageable in the subsequent working phases. For this purpose, the Autodesk Infraworks software® was used to perform the geo-referencing of the point clouds. At the same time, several three-dimensional polylines were generated on the roadway from the same point cloud. A special feature of the software was employed to obtain this result, as it can discern distinct intensity areas inside the point cloud detected by MLS, which vary based on the types of surfaces identified during the laser scanner survey. Following the identification of these regions, linear objects are automatically identified and located along them, resulting in the previously described three-dimensional polylines. At this stage of the research, the main interest is associated with the characteristic polylines of the carriageway's axis and lane borders, which have been detected and extracted. These elements were used to generate the first Digital Model of the infrastructure's pavement, as parametric objects capable of generating such a model are subsequently extruded along their length. Another essential application of the point cloud is to create a three-dimensional surface that depicts the pavement's surface properties, which can be integrated into the Digital Model. The same point clouds were analyzed and processed to build the digital models associated to the complete elements of the infrastructure. One of the main points of innovation in this study is related to the definition of a methodology useful to incorporate the safety barriers located along the road into the digital model. As the model needs to be informative about the state of the infrastructure, it must be possible to analyze these elements once they are integrated into the model itself, to determine any type of distress that could affect the road's components. For this purpose, the same procedure previously described was repeated, to generate three-dimensional polylines corresponding to the base and the top of the safety barrier, so they could also be targets for the parametric objects used to develop the model (Fig. 2a). On the other hand, the data extracted from the static laser scanner were processed by means of point cloud segmentation in order to model other structural elements of the infrastructure, including the piers and foundations of the inspected viaducts, as showed in Fig. 2b. This procedure is organized analyzing different layers portions of point clouds, which presents similar characteristics. For this purpose, the software Recap ® was used to obtain the digital model of the terrain surrounding the structure and the scaffolding, while QGIS and RStudio software, were used to identify the areas of the abutments and piers of the viaduct and extrapolate the point cloud. Through the modeling of parametric objects, it was then possible to model every part of the structure.

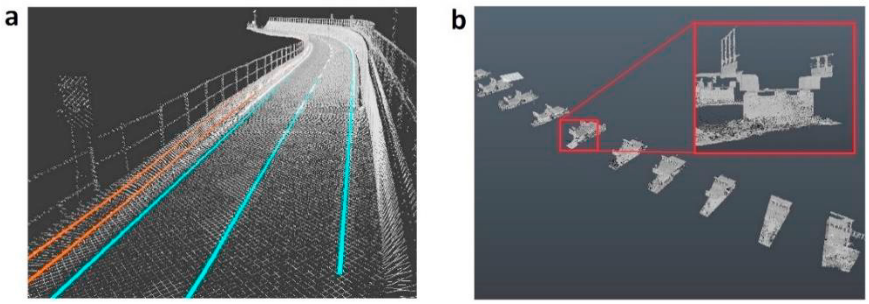

Fig. 2. (a) polylines extraction from point cloud for road markings (blue) and barriers (orange); (b) point cloud segmentation to isolate the areas surrounding the piers of the viaduct.

3.3. Digital modeling

The phases related to the generation of the digital model of the selected inspected road were implemented using the software Autodesk Civil 3D®. The first phase of the process is related to the creation of an alignment generated using the central three-dimensional polyline retrieved from the point cloud that corresponded to the road axis markings. In this way the road digital model can match both the planimetric and altimetric features of the existing infrastructure. After this phase, the second step is aimed at generating the Digital Model, specifically designed employing several parametric objects. These can adapt their dimensions to specific targets, such as the three-dimensional polylines, as described in the previous paragraph. As a result of the applications of the proposed methodology to the available NDTs data, both the pavement and the safety barriers of the infrastructure were modeled and implemented in the digital model. More specifically, the pavement's digital model is composed of three main superimposed planes that constitute the superstructure package. Furthermore, one of the main advantages of the BIM model, is associated to the possibility to reproduce the irregularities of the pavement's surface, since it can adapt to the digital surface with a millimetric accuracy, as it is created directly from the point cloud detected by the Laser Scanner surveys. Moreover, the elements corresponding to the barriers can adapt their position in relation to the infrastructure, reproducing both the distance of the barriers from the edge of the carriage and the information of the tilt by targeting and modeling the three-dimensional polylines, extracted from the point cloud, that represent the base and top of the barrier (Fig. 3). Detailed information about the real inspected infrastructure, associated to the materials, that compose the road superstructure, the location of detected distresses and damages of the modeled carriageway, can be attributed to the model. Several analyses can be carried out to analyze distresses that could affect the infrastructure, such as the model presented can be integrated with information regarding the state of the infrastructure.

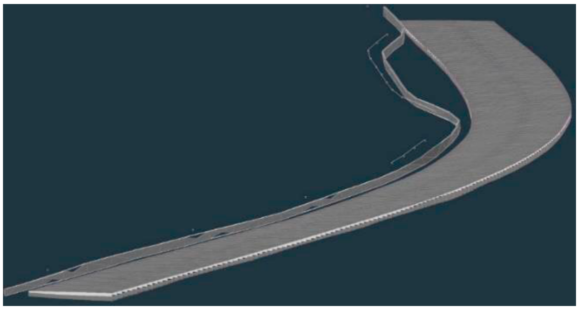

Fig. 3. detail of the model in which both the pavement and the barrier are visible.

The application developed for the modeling phase enables the creation of three-dimensional surfaces directly upgradable using the model's coded links. A specific code was assigned to every layer of the pavement in order to generate a three-dimensional surface. A preliminary analysis was performed to assess the trend of the slopes of these surfaces to determine the most probable outflow of platform waters, and those that are moved away by the draining pavement. In this way, it is possible to detect potential critical issues related to the presence of cracks and potholes on the surface and the location of pavement distresses in the deeper layers, assessing the risk associated with the structural integrity of the road. In addition, the consideration of these issues becomes more critical when they occur on the surface layers of the pavement, which can affect the safety of road users, especially motorcyclists (Fig. 4a). In addition, these analyses can be carried out on the modeled barriers, to determine if their position could be considered incorrect compared to the designed phase, and subsequently plan maintenance activities to correct the situation. In particular, a direct application of the developed digital model is related to the automatic check and the definition of critical alerts, which can be performed in relation to the distance of the barrier from the edge of the carriageway and its tilting. Subsequently, after the definition of a critical threshold value for both these measures, the model can be used to determine the presence of potential critical issues, displaying and localizing these problems over the infrastructure (Fig. 4b). Furthermore, the information associated with the digital model can be extracted and converted into a text file, containing all the reports of errors found in the configuration of the barriers, with an indication of the kilometer of the infrastructure where they occur. Furthermore, the definition of the percentage can be assigned to the accepted error for both the measures checked. The issues become crucial if considered for the planning of maintenance activities at the network-scale level, improving the efficiency of the current procedures implemented by asset owners and administrative authorities.

The process previously described can be also implemented for modeling the substructure of viaducts and bridges starting from the point cloud obtained from the TLS survey. For this purpose, a specific method has been developed based on the implementation of a customizable and programmed script to create a parametric BIM model that automatically reads the geometric data obtained by MLS data and subsequently models the geometry of the structural elements. The modeling of the elements of the bridge represents a principal step to reach the objective of the presented study. The first step consists in the creation of a group of parametric objects that characterizes the modeling element including information related the geometry of the modeled bridge and subsequently become informative.

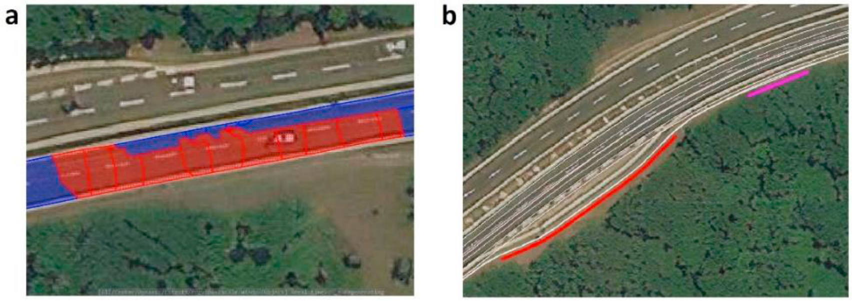

Fig. 4. (a) drainage basins on a layer of the pavement with an indication of those that form a depression (red areas); (b) display of where errors in the barrier's positioning are defined (color-coded depending on the type of error found).

The software implemented for this phase is Revit (Autodesk ®). The next phase of the proposed methodology is related to the use of group elements named "adaptive components", which makes it possible to model the bridge based on a selected reference point defining the position of the elements in the global system, obtaining a digital object representative of the bridge's element including deck, piers, and abutments (Fig. 5a). To manage information of the digital model, automatizing the digital model creation and the updating process, the visual programming software Dynamo® was implemented allowing the customization of the workflow within the Revit application, operating as an add-on programming module for computational design. It allows to code in the Python language using nodes, as reported in Fig 5 b.

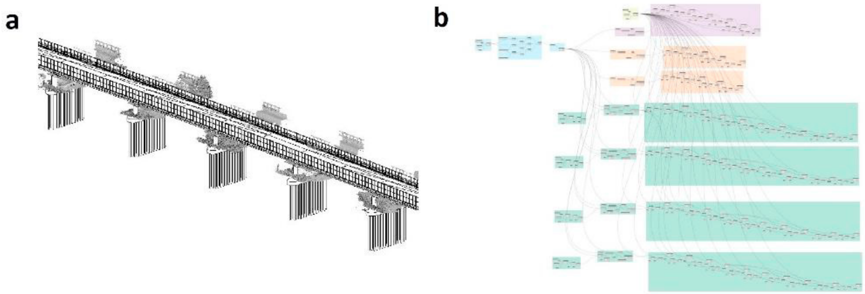

Fig. 5. (a) portion of a digital model of a viaduct with the segmented point cloud over the piers (b) Dynamo script.

4. Conclusion and future perspective

The primary goal of this work was to define a possible viable methodology for integrating multiple datasets generated from non-destructive surveys performed on linear transportation infrastructure. The integration of Laser Scanner and GPR data was completed successfully using several software tools, yielding a digital model of the analyzed road and some of its components. The laser scanner's point cloud enabled the specification of the model's size and position in a georeferenced system and the reconstruction of several elements of infrastructure assets. The GPR data was utilized to calculate the thickness of the pavement layers. The generated digital model was utilized to perform relevant analysis on the state of the infrastructure, even in locations normally inaccessible to operators, such as the deep layers of the pavement. The findings thus far offer a starting point for what the proposed methodology can accomplish. Such a methodology guarantees the data collected on a particular asset to be stored in a single environment over time. This would allow the infrastructures' administrators to effectively schedule the necessary maintenance activities. Possible enhancements to the modeling process hereby presented could be the implementation of other types of survey data into the model, such as the International Roughness Index (IRI) of the pavement or any other useful information regarding the state of the infrastructure and its component. Further research developments can be implemented with the aim to analyze the interoperability between different applications and software. Future studies could analyze the model and its updates after new rounds of surveys or maintenance activities, to better understand how to use it to define the variations of distresses over time. Moreover, the distresses identified should be better analyzed, possibly by comparing other survey results. In this regard, a very interesting development could be the integration of Remote Sensing data, provided by satellites, into the digital model. This information could better specify if distresses detected on the infrastructure are caused by larger problems regarding the area in which the road is located. Integrating these potential improvements into the process would increase the amount of detail in the BIM model, allowing for integrated management of the various infrastructure parts, reaching the concept of Digital Twin.

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