Study of the Application of Terrestrial Laser Scanning for Identification of Pathologies in Concrete Structures

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Research Article

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Abstract

Laser scanning enhances classic field surveys. The terrestrial laser scanner is a versatile device with applications in various areas of knowledge, which uses remote sensing fundamentals to determine point coordinates. It is a remote, active, noninvasive, nondestructive and high-precision technique to capture reality that records from thousands to millions of points per second in a detailed representation of the situation called a point cloud. The surveys are performed along the object of interest in a process called scanning, which has as its gross product a dense cloud of three-dimensional points of the scanned object. This point cloud stores information about the object's geometry, return pulse intensity, and point color data. As a way of extending the uses of terrestrial laser scanning, this work studies the application of this method in civil engineering, through the identification of pathologies in reinforced concrete structures, aiming to show how geoinformation can be employed in this area. To this end, a case study of the São Cristóvão Viaduct was conducted in the city of Rio de Janeiro. This study included definition of the site of analysis; planning and execution of the field survey to collect raw data; processing of the point cloud; and generation of a three-dimensional surface for global visualization of the structure and identification of pathological manifestations and the regions where they were observed. Concrete structures in general are affected by various external factors, such as weather and anthropogenic actions, which contribute to their wear.

1. Introduction

The technology using laser scanners is an improvement for field surveys. In classical topography, using angles and displacements in three-dimensional surveys, the final objective is to determine coordinate points. Initially, terrestrial surveys used theodolites and the technique was efficient when introducing electronic measurements of displacement and directions. The integration between both techniques led to total stations, employing reflective prisms to determine three-dimensional coordinate points on terrestrial surfaces. Subsequently, the evolution of laser measurement allowed finding three-dimensional coordinate points without prisms. These points are calculated remotely, which is useful mainly in places with difficult access or risk to the operator's safety. These factors led to the development robotic total stations, where coordinates can be measured without operators (Wutke, 2006).

This characteristic makes TLS a versatile technique, with various applications, such as engineering, architecture and geology. Besides that, the equipment has high data acquisition rates (thousands or millions of points per second), which can provide high agility at construction sites. Moreover, the high acquisition generates a large quantity of data on the structural feature of interest. This is a noninvasive and nondestructive technique, where there is no contact between the equipment and the object of analysis (Pavi et al, 2014).

Reinforced concrete structures in general develop pathologies due to external factors, such as weather and human actions. In Brazil, analysis of the structural integrity of concrete structures is deficient, leading to precarious conservation due to the failure to detect pathologies and avoid disasters such as building collapses. In this context, the use TLS for semi-automatic detection and classification of pathologies can be a relevant advance to prevent disasters.

In recent years, several applications of the Terrestrial Laser Scanning (TLS) and the point cloud generated from it have been studied by countless authors, aided in large part by the intense technological development of the last two decades. Among the application areas of TLS, they stand out in engineering and architecture, infrastructure, in industry, in mining and geology, archeology, ecology, medicine and in the forensic and agricultural sectors. In engineering and architecture, the generation of as-built and 2D plans, interior design, 3D modeling (Pu and Vosselman, 2009) and integration with BIM (Building Information Modeling) technology, structure monitoring (Godycka et al.,2014) and interventions in existing structures.

As mentioned by Pavi et al. (2014, p. 8-10) and Lubowiecka et al. (2009), used the laser scanner in the dimensional and structural analysis of a spanish bridge. Pesci et al. (2011) analyzed deformations and deviations of structures from TLS data. González-Jorge et al. (2012) used the terrestrial laser scanning to detect the presence of biofilm and moss proliferation in reinforced concrete structures.

Teza et al. (2009) developed a computational method to identify surface damage caused by loss of mass in reinforced concrete structures. Rabah et al. (2013) used the TLS to detect and automatically map cracks in concrete surfaces. Brandão (1998) studied its application to buildings.

In topography, it has great utility in planialtimetric topographic surveys, calculation of volumes, maps and generation of topographic profiles and Digital Elevation Models – DEM (Meouche et al., 2013).

In this case, the objective was to determine areas at risk of flooding in urban zone. Wutke (2006, p. 15) mentions applications in geotechnics and geophysical modeling. It also mentions studies in reverse engineering, prototyping, aeronautical, vehicles, vessels and large objects in general modeling. It is also used in the documentation of industrial plants, in mining, with calculation of ore volume, in studies of natural risks and verification of underbreak and overbreak during tunnel excavation (Gonçales, 2007). Fekete et al. (2010) used the TLS to scan tunnels in the process of excavation and drilling. There are also studies on the documentation and preservation of historical heritage. In the forensic sector, it is used to reconstruct crime scenes.

According to Giongo et al. (2010, p. 231), the TLS can be used in coastal planning, flood risk assessment, telecommunications and energy transmission networks. It is also possible to use it in agriculture and in the oil sector, transportation and urban planning. In medicine, Dalmolin and Santos (2004, p. 89) mention the design and manufacture of prostheses and comparative studies of volume and surface textures before and after surgeries.

Mugnai et al. (2019) presented a research study designed to assess the health status of a medieval bridge built on 1500 under the Medici dynasty over the river Sieve, close to Florence, using Terrestrial Laser Scanning (TLS) to identify anomalies and deformations. Marzouk et al. (2019) proposed a framework with TLS data and BIM models in order to overcome the weaknesses of the traditional methods in Egyptian Heritage called Tosson Palace. Takhirov et al. (2019) used the high-definition laser scanning technology in an extensive structural assessment of historic monuments in Uzbekistan.

Shafikani et al. (2019) showed an application of TLS technology for assessing the performance of bridge infrastructures, including highway embankments, bridge decks, approach slabs, abutments, and columns supported on drilled shafts. This application also studied the ground movements. Cha et al. (2019) introduced a practical feasibility study of a shape information model to monitor deformation or deflection of bridge structures using TLS. Finally, Carvalho (2019) presented a case study of the application of the terrestrial laser scanning in the identification of structural pathologies in an viaduct.

Armesto et al. (2010) developed a methodology using TLS to estimate the deformation of arches or vaults based on the symmetry of sections obtained along the vault guideline. TLS technology applied to register as-built projects can be found in Tang et al. (2010), Brilakis et al. (2010) and Bosché (2010). Armesto-González et al. (2010) presented a methodology to combine the technology of the terrestrial laser scanner with the techniques of digital image processing in order to study damages on stony materials that constitute historical buildings.

In addition to the Civil Engineering field, the are several another applications of TLS technology as described below among others:

• architectural restoration of iconic buildings, such as the Glass House, built in the 1950s, as well as the MASP Structure Conservation Plan, both in the city of São Paulo;

• documentation and renovation of the Malé Hukuru Miskiy, located at Malé city in the Republic of Maldives

• based on the fire that almost destroyed Notre Dame Cathedral in Paris a lot of other Museums, Heritages, Opera Houses and other iconic buildings are investing in this scope of work.

• volumetric measurement of chemicals products in storage sheds;

• elaboration of three-dimensional electronic model and architectural plans on a large scale map;

• planialtimetric mine survey for mining planning and track of tunnels; and

• new experiences and services for real estate market: accurate floorplans for customers to know exactly what they are paying for.

So, the general objective of this work is to study the applicability of terrestrial laser scanning for identification of pathologies in reinforced concrete structures, to demonstrate how remote sensing can be used in civil engineering in complementation with visual inspection to improve detection of pathologies and thus conservation of structures.

This article is divided into three more sections. Section 2 outlines the results of the evaluations of the normalized point cloud of the São Cristóvão Viaduct, as well as the three-dimensional model prepared from it and the classification made. Section 3 presents in greater detail the normalized point cloud and the three-dimensional surface generated for the São Cristóvão Viaduct. Finally, Section 4 presents our concluding remarks.

2. Results

This section presents and comments on the results of the evaluations of the normalized point cloud of the São Cristóvão Viaduct, as well as the three-dimensional model prepared from it and the classification made. Thus, the objective was to determine the possibility of identifying these pathologies through the point cloud and these products, shown below.

2.1 General Characteristics of the structure studied

The structure chosen for analysis was the "Old" São Cristóvão Viaduct, located in the district of the same name in the northern zone of the city of Rio de Janeiro. The viaduct overpasses train and metro lines and is located next to the Oduvaldo Cozzi Viaduct.

The viaduct is made of reinforced concrete. Its structural arrangement comprises a total of 6 longitudinal beams along its length. These beams receive the forces coming from the slab over which vehicles circulate. The structure is segmented into six spans, one on the side of the Maracanã district (access), one above the Rio Metro railway line (aboveground extension of the subway system), two above the Supervia railway line (metropolitan commuter trains), one above General Herculano Gomes Street and one on the way down the viaduct, next to Quinta da Boa Vista Park. Each span is separated from the adjacent one by a transversal line of six pillars each, which bear the forces from the six longitudinal beams. Additionally, each span has 5 transversal beams (perpendicular to the longitudinal beams), which also receive loads from the slabs, as shown in Figure 1.

2.2 Field Survey

The survey took place on May 27, 2019, and lasted approximately 2 hours. According to the geometry of the viaduct structure and the positioning of the station platforms in relation to it, 14 equipment position points (setup points) were determined. Additionally, a fifteenth point was defined outside the station, on the sidewalk of General Herculano Gomes Street, in order to generate a cloud of points in this region of the viaduct. Thus, the survey generated 15 scenes, as shown in Figure 2, that is, 15 different point clouds, one for each point where the device was positioned.

In this work, we chose to use the device with medium acquisition rate. In this way, the taking of photographs in each scene lasted approximately 3 minutes. The scanning of each scene lasted approximately 4 minutes, totaling approximately 7 minutes for each position point.

2.3 Data Processing

At the end of the first scan, the device was taken to the second position point. The scanning process was then repeated for all 15 points where the device was positioned.

Finally, with all the clouds generated, the raw data were processed in the university office. This can be done by any computer that has the minimum computational requirements defined by the equipment manufacturer. In this work, we used a computer with a 6-core processor, 12 MB cache and maximum frequency of 3.8 GHz, along with a graphics card (GPU) of 1GB and 32 GB RAM.

The Leica Cyclone Register 360 software was use for refinement and completion of the scenes. When the program was opened, a new project was created, and then the 15 cloud files were imported. These files are native to the BLK 360 terrestrial laser scanner, and have *.blk extension. This way, it was only possible to open them with the Leica proprietary software, from which they are exported to other formats. In this work, each cloud file had approximately 354 MB, totaling approximately 5.31 GB for the 15 files.

The scenes were then recorded between pairs of point clouds, as shown in Figure 3 (a), where each green line indicates a connected and recorded pair. Each of these connections was called a link. For the 15 clouds in this project, 26 links were established.

After creating the 26 links, the process of recording point clouds was completed. From this, the software displayed the recording quality parameters: accuracy (bundle error), overlap and strength, according to Figure 3 (b), and issued a report of the process. At the end of the recording, the consolidated cloud was exported to the open format *.pts. The file was approximately 5.76 GB.

Thus, after all the scenes were recorded, the cloud was reduced so that it only contained points relative to the São Cristóvão Viaduct. This procedure was performed in the CloudCompare program. This is free software for processing three-dimensional point clouds under the GNU General Public License. This reduction consisted of selecting the regions that did not correspond to the studied structure and eliminating them from the cloud, as can be seen in Figure 3(c), in red.

2.4 Consolidated point cloud

After recording the clouds, a single consolidated cloud was obtained, which presented all the elements in the environment around the viaduct, captured by the terrestrial laser scanner during field work.

The consolidated cloud, as can be seen in the Figure 4, although visually attractive, detailed and rich in elements, presented a number of features far superior to the object of study. In this figure, it is possible to see that, besides the structure of the viaduct, data from the station platforms, the nearby Oduvaldo Cozzi

Viaduct, as well as the nearby vegetation, passengers and the Supervia train cars themselves were also captured.

3. Discussion

This section presents in greater detail the normalized point cloud and the three-dimensional surface generated for the São Cristóvão Viaduct, in order to identify of structural pathologies. For this purpose, the viaduct was segmented into 4 sections defined according to the position of the pillar lines. For each section, the point cloud, the three-dimensional surface and photos of the corresponding region are shown, in order to establish a parallel between the visually identified pathologies and their representations in the products generated from the terrestrial laser scanner survey. This comparison aims to study the applicability of this technique for the identification and cataloguing of pathological manifestations.

The Pathologies identified in sections 1, 3 and 4 during the current study are available from the corresponding author upon request. We present bellow the Pathologies identified in section 2.

Both the point cloud and three-dimensional surface present continuous behavior, mainly in relation to section 1. This continuity can be explained by the location of more points for the survey of this section. It is possible to notice lower occurrence of shadow regions, which stand out near the pillars. Shadows, although less frequent, were caused by the passage and constant stopping of trains during scans, also acting as a physical barrier to the integral capture of the structure of this stretch.

Failures can also be noticed in the external regions of the viaduct, notably at the edges and in the upper portion, near the slab. This behavior is explained by the positioning of the scanner during the scans. As the survey was done from the station platforms, and since the coverage of these platforms extended to the vicinity of the viaduct along the platforms, the field of view to the top of the viaduct was restricted. Also contributing to this failure is the fact that the coverage of the upper part of the viaduct slab was not part of the survey.

The pillars show good representation in the point cloud, given the fact they are located in a region closer to the scanner, thus being hit by the beams orthogonally. The bottom of the slab as well as the sides and bottom of the beams also have good representation in the cloud.

The three-dimensional surface is consistent with the point cloud, showing discontinuities in regions with less point density. Slight presence of noise also can be observed, more frequent in the upper part of the slab, where the open surface and the scarcity of points made the creation of triangular surfaces difficult.

The texture of the surface is uniform and consistent with the structure it represents, with good coverage of the slab and beams. The pillars have accurate representation, consistent with their geometry, including the application of colors to their surface. However, atypical roughness is observed in the external pillars of this section.

Some critical regions can be observed in this section, as seen in the details of the point cloud, Figure 5 – (a), (c) and (e), and the three-dimensional surface, Figure 5– (b), (d) and (f). There are moisture stains along the edges of the slab, at the end of the viaduct, which is also explained by the fact that it is a region more subject to infiltration and percolation of water. These can be better observed in the normalized point cloud than in the three-dimensional surface, which can be explained by the difficulty in creating them. Moisture is also observed in some internal regions of the viaduct slab.

Analysis of the point cloud also shows the existence of slabs and beams in the regions of the structure with exposure of shallow reinforcement (rebar's) on the concrete surface. With the grey scale coloration of the cloud, these regions can be more easily discerned.

Through analysis of the three-dimensional surface, although it is possible to verify the presence of moisture stains and rebar exposure, its identification cannot be done easily and in isolation. However, it is possible to identify the regions where biodeterioration has occurred.

In this section, the slab and beams of the viaduct are more affected, with greater presence of pathological manifestations than the pillars, which in general do not show structural deterioration.

Additionally, besides the analysis of the standardized point cloud and the three-dimensional surface generated from it, we also did a point cloud classification. These classes were defined by selecting samples from the cloud itself, and then applying them to the points in their entirety.

This classification, although still preliminary, aimed to propose a semi-automatic method for identifying structural pathologies from a point cloud. This method allows a quicker field work, and it is especially helpful in situations where people cannot get access to all the structure. Since this is an initial study, for the cloud generated in this work two classes were defined, one for healthy regions, identified by the color red, and another for deteriorated regions, identified by blue, according to Figure 6.

In future studies, it is recommended that the unhealthy class be split into more sub-categories, according to the pathologies found in the structure. This will allow a more assertive global analysis, enabling actions more targeted to each pathology to be taken. In addition, this more segmented analysis can also allow the correct quantification of the areas affected by each pathology.

4. Conclusion

Terrestrial laser scanning (TLS) has applications in several areas of knowledge, notably in engineering. Given the characteristics of the data that this equipment generates, forming a point cloud, it is possible to formulate several spatial products and perform qualitative and quantitative analysis. One application still relatively little explored is its use to identify pathologies in reinforced concrete structures. This is done by scanning the structure of interest and using the intensity and color data of the return pulse collected by the scanner to identify healthy and deteriorated regions. Thus, this work aimed to study the applicability this equipment in civil engineering, to support maintenance programs of buildings other structures.

Based on the bibliographic research of the theoretical bases that underpin TLS, its operating principles, characteristics and applications present in the literature, as well as concrete structures, their types, composition and main degradation processes, it was possible to confirm the theoretical relation between the two themes. In order to deepen the study of this relation, we presented a case study of a viaduct made of reinforced concrete.

By analyzing each point cloud after the elimination of features, it was possible to observe good general representation of the viaduct structure. In some regions, however, especially in sections 1 and 4, significant discontinuities in the cloud and shadow regions, caused by the presence of physical barriers at the time of the survey, were noted. These barriers consisted of partition walls and the presence of moving trains, people and vehicles during the scanning. Although this did not make the work impossible, such barriers and impediments resulted in areas with sparser data, so that the overall analysis of the structure was impaired.

The use of the terrestrial laser scanning for the identification of structural pathologies is a clean alternative for monitoring and inspection of concrete structures. It is a nondestructive and noninvasive method where, besides not generating damage to the evaluated structure, does not produce any waste to be discarded in the environment. Moreover, the most relevant characteristic of the technology is the great speed and quality in data collection. In general, this technique enables the evaluation of pathologies in the structure to be improved quantitatively and qualitatively. Thus, better evaluations result in more corrective maintenance and major repairs, with the benefit of extended lifetime and greater safety.

Declarations

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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- Leonardo Vieira Barbalho, M.Sc. (Data curation: Lead; Methodology: Supporting; Software: Supporting; Validation: Supporting)
- Lucas de Campos Rodrigues, Engineer (Methodology: Supporting; Resources: Lead; Software: Lead; Visualization: Supporting)

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Figures

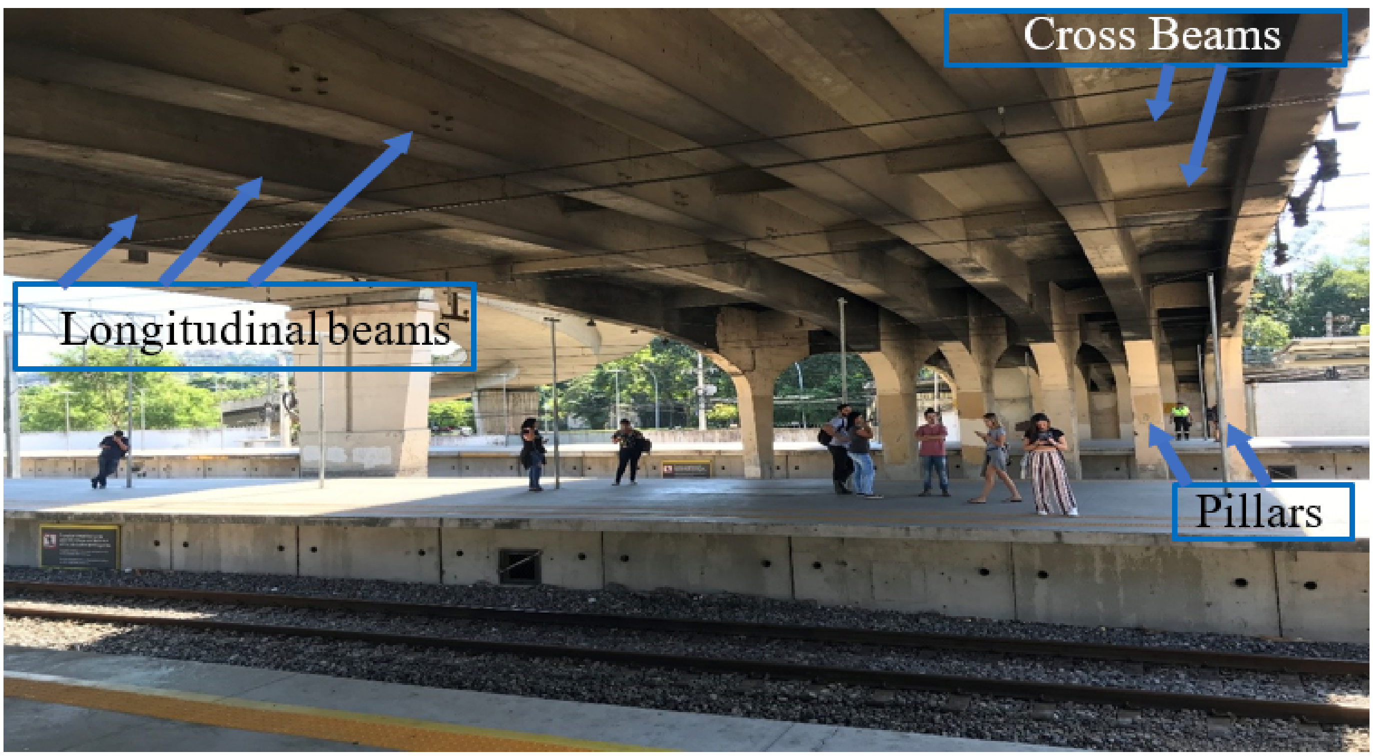

Figure 1

Structural arrangement of São Cristóvão Viaduct

Figure 2

Schematic representation of the 15 position points of the equipment (Google Maps, 2019)

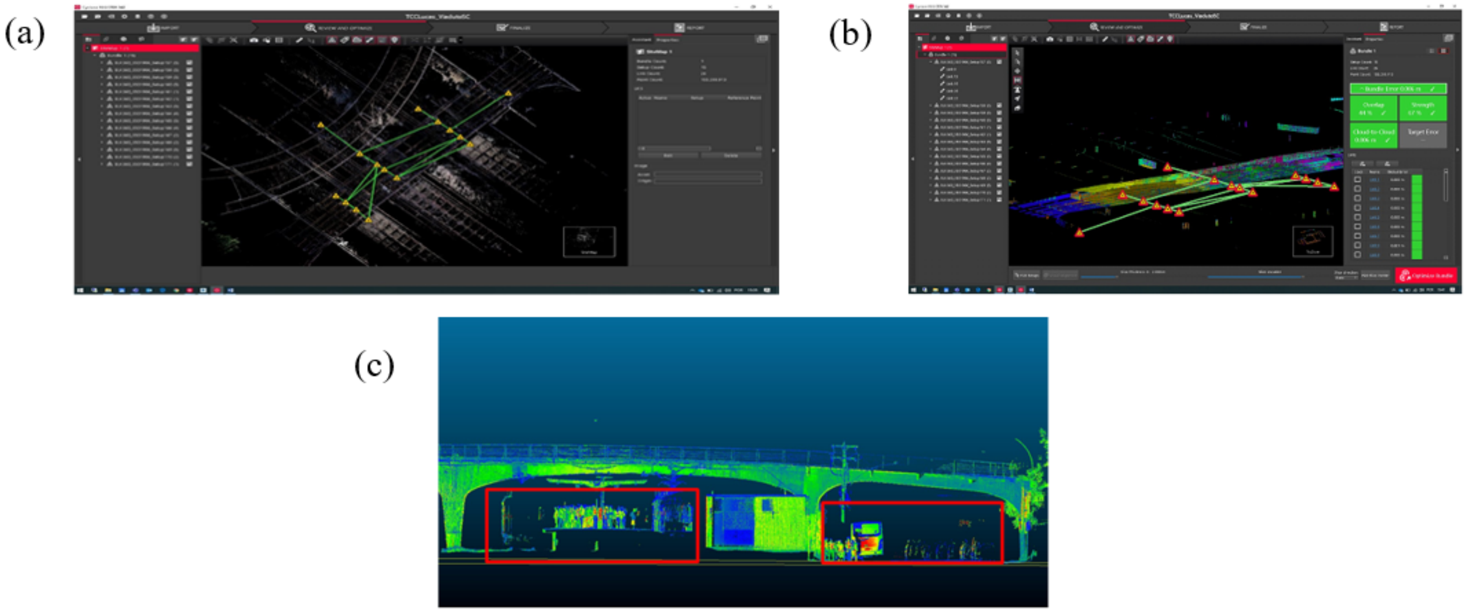

Figure 3

(a) Scene registration. (b) Conclusion of the cloud recording process (c) Elimination of features in CloudCompare software.

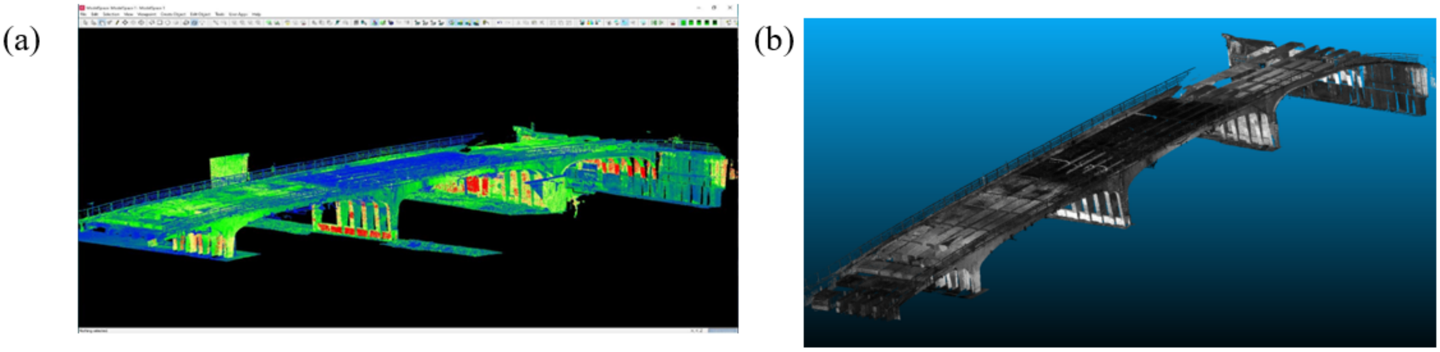

Figure 4

(a) Point cloud after recording and cleaning. (b) Normalized point cloud, in gray scale.

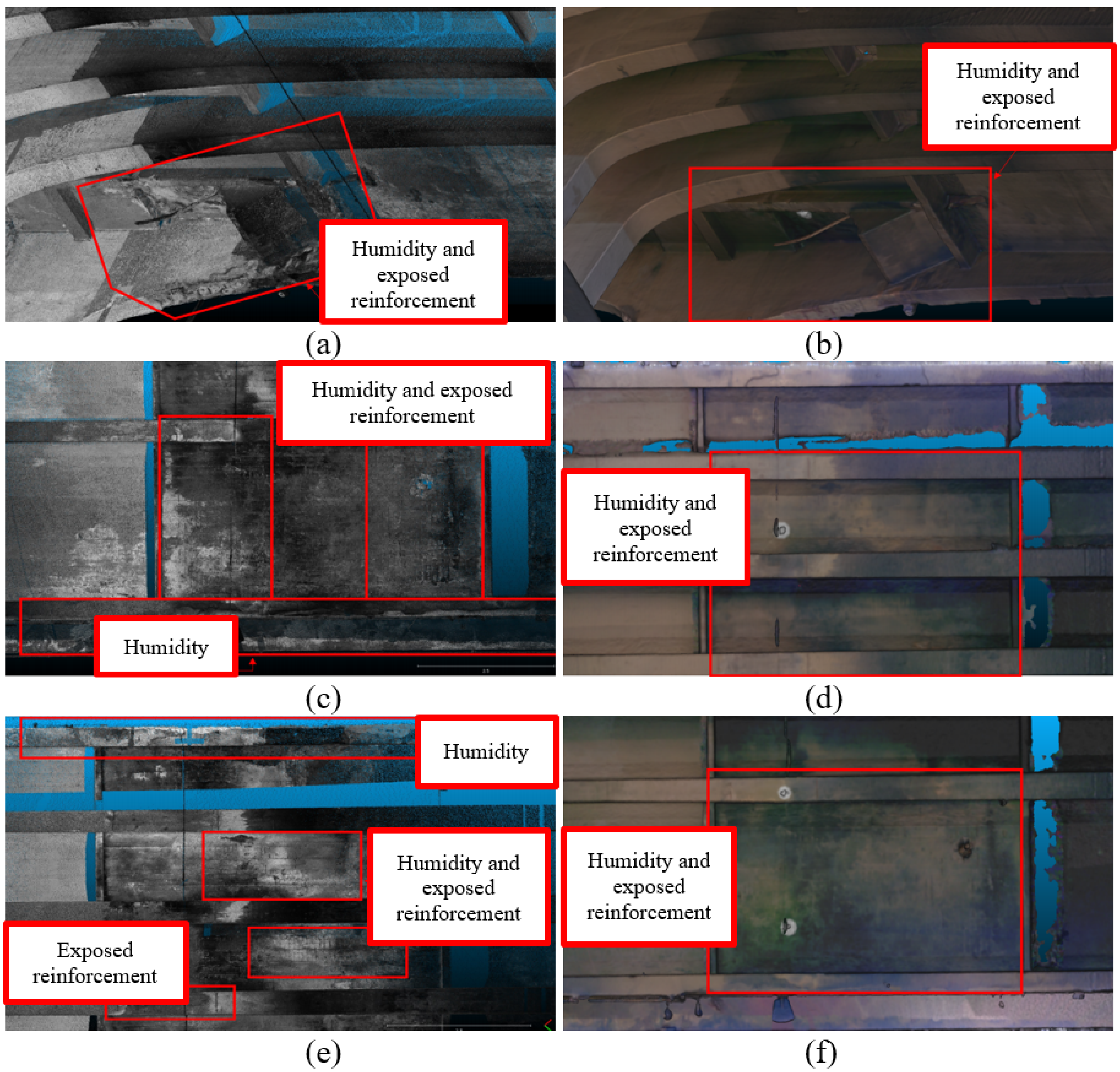

Figure 5

Pathologies presents in the viaduct. (a), (c) and (e) – Gray scalar; (b), (d) and (f) Real Color

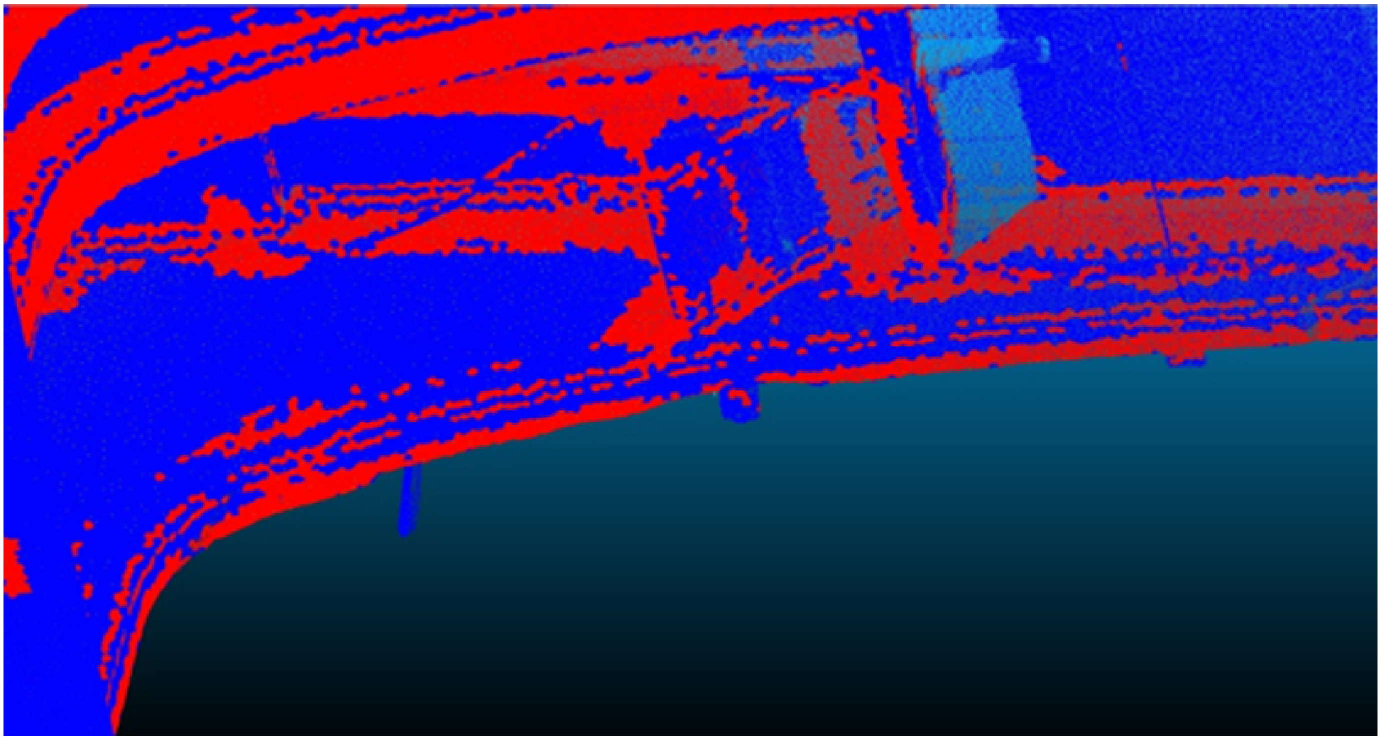

Figure 6

Classification of the cloud for part of section 2