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ASSESSING THE SURFACE CORROSION OF A STEEL RAILWAY BRIDGE USING AN ACTIVE SHORT-RANGE REMOTE SENSING SYSTEM

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Summary

The idea of assessing the surface corrosion of a steel railway bridge evolved as a response to an industry need for *fast* and *non-manual* confirmation of the progress of surface deterioration of monochromatic bridges. Terrestrial laser scanning is a technology for remote acquisition of information about the geometry of an object in the form of a point cloud, in which the coordinates (X, Y, Z) are recorded for each point and information on the intensity of the reflected beam is also recorded. In addition to the accurate representation of changes in the geometry of an ageing object, represented by the three-dimensional coordinates of the bridge, terrestrial laser scanning provided information about the surface properties of the bridge object in the form of the intensity of the reflection beam. Imaging algorithms enable it to indicate the homogeneous surfaces of the bridge and, therefore, suggest whether they are subject to corrosion processes or not. The intensity of the object's point cloud, through the use of unsupervised classification tools, ensures the detection of changes in the surface properties of a monochromatic railway bridge. The classification method for the unsupervised raster representation of grey-scale reflectance intensity (generated from TLS data), as in classical remote sensing, provides classes of pixels with similar reflectance properties. The concept for the scientific research on the detection of the corrosion progress of a steel railway bridge using an active short-range remote sensing system involved the development of algorithmic advances that allow the comparison of periodic raster classifications from a point cloud. Thanks to the differentiation of the imaging, it is possible to determine changes in the location and extent of corrosion, the rate of its progress in ageing steel objects, the detection of cracks and fissures as structural hotspots, indicating the filling capacity of the object, as provided for in the technical documentation. The study provided an empirical basis for research on automatic corrosion detection.

Keywords

terrestrial laser scanning • TLS • reflectance beam intensity • unsupervised classification • Fuzzy K-Means

1. Introduction

The problem of stability of steel railway bridges with regard to their material durability and in the context of the introduction of high-speed rail in Poland is still a topical issue [Gawronek and Makuch 2019, Gawronek et al. 2019]. According to the maintenance policy for railway bridges, the durability of steel structures is guaranteed by their appropriate design, construction, maintenance, and preservation over their expected life, which, according to the requirements of European standards, is 100 years [Siwowski and Rajchel 2021]. Currently, in Poland, a considerable part of the railway bridge infrastructure has reached the upper limit of the time for which it was designed. These structures, usually engineered for loads lower than the actual operating loads, are undergoing accelerated structural degradation as a consequence of material fatigue. The material strength of steel girders of railway bridges assumed by PKP PKL S.A. does not exceed 100 years of service. The age of railway bridges for almost half of them has reached a level of advancement that meets the life expectancy expected in technical designs [Bień 2010]. Professor Jan Bień of the Wrocław University of Technology refers to the existing condition as *pathology and technical geriatrics* of bridge structures [Bień 2010].

Steel is a material with a homogeneous structure and high elasticity coefficient, thanks to which the operational safety of steel structures is ensured. A phenomenon that has an adverse effect on the strength and durability of steel is its corrosion, which occurs through oxidation of the metal [Coca et al. 2011]. Bridge structures with load-bearing solid or lattice girder systems can suffer significant damage from atmospheric corrosion. Estimating the effect of corrosion on the durability of bridge structures is a complex procedure that mainly requires determining the type of corrosion and the size of corrosion pits [Liu et al. 2001, Jin Lim et al. 2021]. It is also important to: identify the areas of corrosion on the load-bearing surfaces of steel elements; detect the effects of the corrosion process in the form of cracks and fractures; determine the uneven distribution of corrosion products and the associated loss of structural steel in the cross-sections of load-bearing elements. The corrosion phenomenon and the cyclically varying stresses cause together a much greater reduction in the load-bearing capacity of the structure than the actions of each factor alone. The alternating stresses intensify corrosion, and corrosion accelerates the fatigue development of the structural material [Bień 2010, Śpiewak and Ulewicz 2016].

A terrestrial laser scanner is an active remote sensing device that allows the determination of the coordinates (X, Y, Z) of a specific object based on electronic measurement of distance and angle [Wider and Gawronek 2021]. In addition to the spatial representation of the object in the form of a point cloud, for each of its elements the value of the intensity of the reflectance beam is recorded, which represents the degree of absorption of the laser light by the surface of the measured object. The dependence of the intensity of the reflected radiation on the nature of the reflecting surface, its colour, roughness or moisture content, makes it possible to carry out detailed analyses of its condition and, in principle, enables the detection of changes in the surface of the object [Gawronek and Noszczyk 2023].

The notion of assessing the surface corrosion of a steel railway bridge was born as a response to an industry need for a rapid and non-manual account of the progress of surface deterioration of the structure. A study of the stability of railway bridges using terrestrial laser scanning was intended to determine the periodic displacements [Gawronek et al. 2019] and during static load tests [Gawronek and Makuch 2019] of a centuries-old, monochromatic steel bridge. The results of determining the displacements from the precise cloud model of the object proved satisfactory for the railway industry, but the question then also arose as to whether a 3D mapped object beyond the geometry could provide information about the surface condition of the bridge. This discussion with industry needs defined the aim of the paper: detecting the corrosion process of a steel, old railway bridge on the basis of periodic point clouds of the object and using remote sensing techniques for automated image recognition. In addition to the accurate representation of changes in the geometry of the ageing object, represented by the three-dimensional coordinates of the bridge, terrestrial laser scanning does, after all, provide information about the surface properties of the bridge object in the form of the intensity of the reflectance beam. The fourth coordinate of the point cloud, through the imaging algorithms, should therefore indicate the homogeneous surfaces of the bridge and, therefore, whether or not it is affected by corrosion processes.

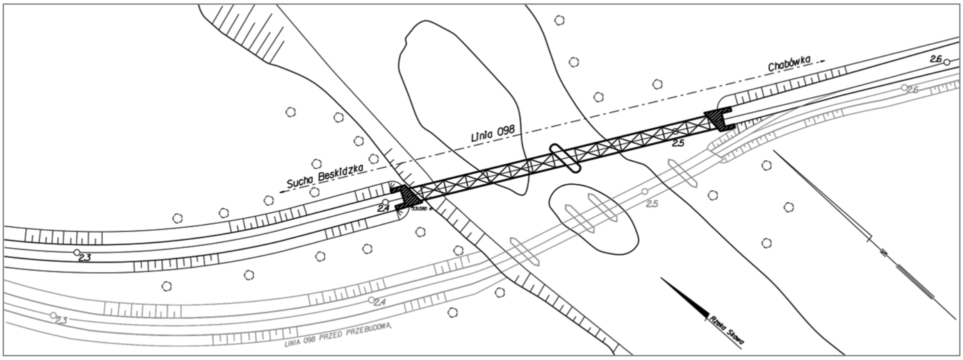
The notion of assessing the surface corrosion of a steel railway bridge using an active short-range remote sensing system is presented in four parts of the paper. The introduction characterises the industry need for monitoring the condition of steel railway bridges and identifies the potential of TLS technology. ‘Materials and methods’ section describes the study object, the data used in the remote sensing analyses and the method of study design. The ‘Results and discussion’ section includes the results of the corrosion surface imaging for the analysed test field. The conclusions of the study are summarised in the final section of the article. The summary also previews research on surface corrosion detection based on data acquired from various sensors.

2. Description of the conducted research

Object

Studies on surface corrosion detection from point clouds were carried out for data acquired in three measurement series for a monochromatic steel railway bridge, located at kilometre (km) 2.485 of railway line No. 098 Sucha Beskidzka – Chabówka (Fig. 1). The discussed bridge was built in the 1960s during the modernisation of the railway route, intended to raise the course of the then existing gradeline of the railway track running over the bed of the Skawa river (Fig. 1). The legal basis for the investment was provided by Technical Standard D – 64 of 1956.

The structure of the railway bridge consists of a two-span continuous superstructure with a theoretical span: 52,700 m + 52,700 m = 105,400 m (Fig. 2). The railway bridge structure is founded on concrete diagonal abutments and a pillar. To smooth the displacement of the bridge’s continuous superstructure at the supports, a sliding and non-sliding spherical plain bearing assembly is used. The longitudinal axis of the bridge crosses the axis of the obstacle at an angle of 55°. The total width of the railway bridge is 5,400 m. Single tracks with a gauge of 4,500 m run across the object.



Source: Author's own study. Prepared on the basis of vectorisation of documentary sketches of the redevelopment of the project

Fig. 1. Location plan of the bridge at km 2.485 of the railway line No. 098 Sucha Beskidzka – Chabówka

The study of railway bridge stability and the detection of surface corrosion required careful selection of the test object. Steel, multi-span railway bridges form the basic infrastructure of rail transport in Poland [Klasztorny 2005]. Common bridge structures were usually built in the middle of the 20th century. Due to ageing and rheological processes, which result from a long service life, they require more detailed inspection measures [Klasztorny 2005]. The railway bridge at km 2.485 of the Sucha Beskidzka – Chabówka route is a justifiable representation of the most numerous group of rail transport bridges.

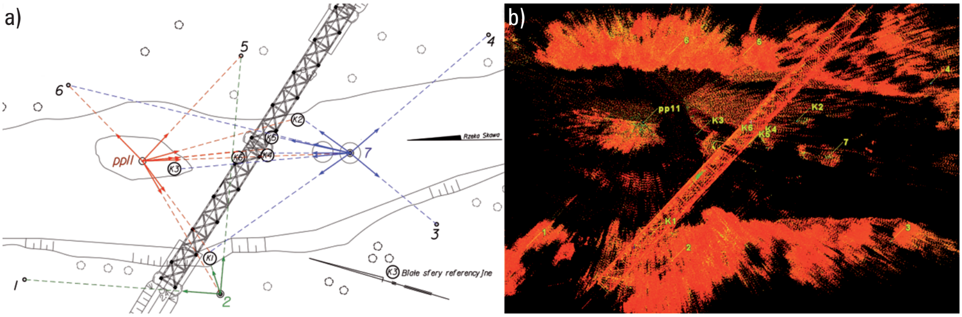
Terrestrial laser scanning

TLS measurements of the railway bridge were taken in three measurement series, with an average time interval of one year. Laser scanning was carried out with a Z+F 5010 scanner with reference to the points of the object's matrix, designed to test its stability. The results of the studies were 3 point clouds of the object in the matrix system, whose mean registration error RMS did not exceed ±1 mm (Fig. 2, 3, 4). This figure also characterised the mean errors of the binding points of the measurement stations.

Detection of surface corrosion

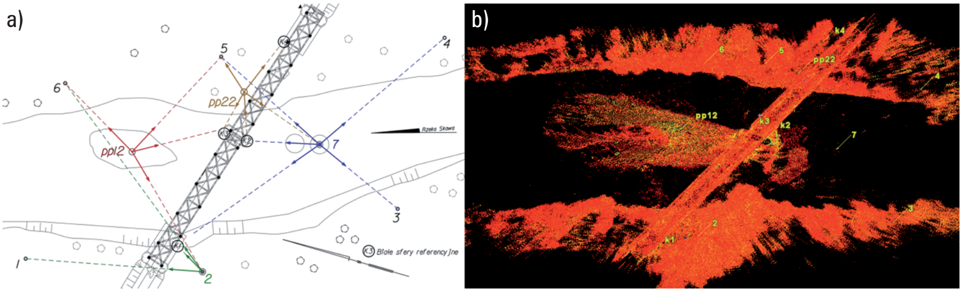
The detection of surface corrosion of a monochromatic, ageing railway bridge was done for a test field representing the population of the lower structural nodes of the object (Fig. 5). The selection of the test field for the spectral analyses was motivated by the accumulation of rusts in the lower nodes of the steel structure.

In the spectral detection of surface changes, a number of factors have to be defined that affect the changes in the imaging and can therefore cause artefacts in the results. The intensity of the reflectance beam depends on the reflecting surface: its material, colour, roughness, moisture content and contamination in the form of degradation organisms. The final spectral analysis influences the conditions and procedure of TLS



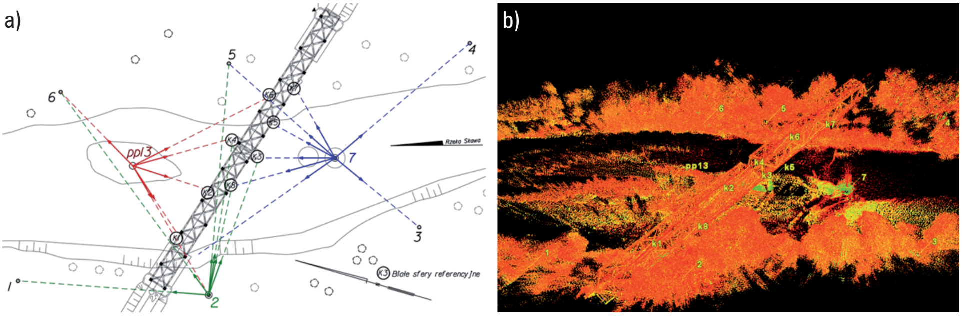
Source: Author’s own study

Fig. 2. Distribution of survey stations and reference points during the TLS of the bridge: Series I; a) TLS measurement outline; b) Point cloud after registration of stations



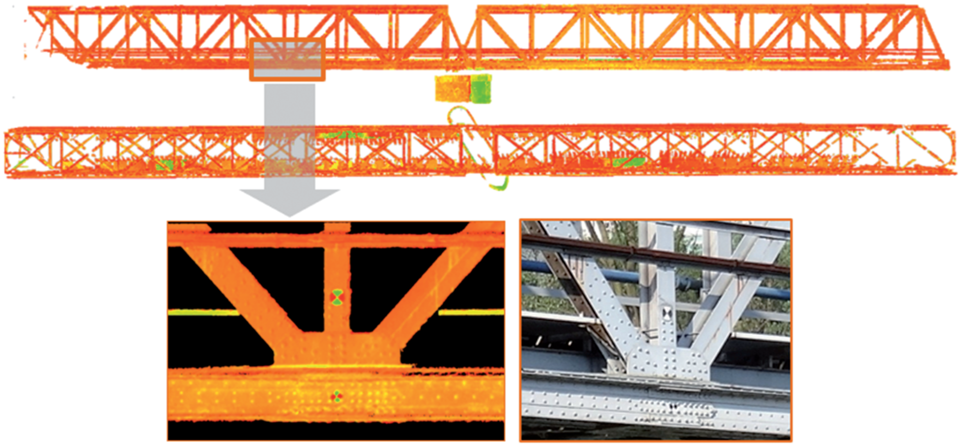
Source: Author’s own study

Fig. 3. Distribution of survey stations and reference points during the TLS of the bridge: Series II; a) TLS measurement outline; b) Point cloud after registration of stations



Source: Author’s own study

Fig. 4. Distribution of survey stations and reference points during the TLS of the bridge: Series III: a) TLS measurement outline; b) Point cloud after registration of stations



Source: Author's own study

Fig. 5. Test field for spectral analyses

POINT CLOUD POST-PROCESSING

1 scanning station

→ elimination of standardisation of reflectance beam intensity vs. incidence angle of the laser beam from successive scanning stations

3D data filtering

Point cloud orthoplans

→ for selected and compared corrosion areas

UNSUPERVISED CLASSIFICATION

Definition of spectral channels

Unsupervised classification

→ Fuzzy K-Means algorithm, empirical determination of pixel classes in the classification process

COMPARATIVE ANALYSIS

Detection of corrosion progress

→ Analysis of the number of epoch pixel classes, classified rasters, as a detector of the progression of the corrosion process of steel

Source: Author's own study

Fig. 6. Surface corrosion detection scheme from TLS data

measurement and point cloud postprocessing (Fig. 6), in which certain assumptions have to be kept, e.g. the surface analysed on the point cloud raster should be obtained with the same measuring instrument and should not be damp during the measurement. Meeting the assumptions allows for a reliable assessment of the surface changes of the object over time. Although analysed rasters obtained independently of these assumptions could also participate in qualitative surface analyses through unsupervised classification, this process would have to be preceded by a laborious process of data filtering, bringing them to a common ground in terms of these two conditions.

Among the most efficient algorithms for unsupervised classification, Fuzzy K-Means has been dominating for years. *The algorithm defines a probabilistic value of the corresponding image pixel belonging to each cluster, and gives particularly good classification results for pixels located between cluster centres* [Mitka et al. 2016]. By adopting unsupervised classification with the Fuzzy K-means algorithm, image pixels are grouped into a preset number of classes, so that the analysis of image scenes with the same properties (texture, colour, etc.) becomes fully interpretable. According to [Sánchez-Aparicio et al. 2018, Gawronek and Noszczyk 2023], the Fuzzy K-Means algorithm minimises the squared distance between feature values of two points that reside in the same cluster. The Fuzzy K-means algorithm determines the centroid of each cluster using the method of the minimum of a sum-of-squares cost function (Eq. 1) by applying coordinate descent.

$$J_q(U,V) = \sum_{j=1}^{N} \sum_{i=1}^{K} (u_{ij})^q d^2(X_j V_i) \qquad K \le N \tag{1}$$

where:

q – any real number greater than 1, representing the weight exponent for u_{ij} and controlling the fuzzying of each cluster,
U – $N \cdot K$ partition matrix, where N is the number of data points, and K is the number of clusters,
V – a set of objects in the same object domain,
X_i – j-dimensional feature vector,
V_i – i-th centroid of the cluster,
u_{ij} – degree of membership of X_j to the i-th cluster,
$d^2(X_j, V_i)$ – distance between X_j and V_i.

Fuzzy partitioning is implemented by iteratively solving the cost function (Eq. 1). This solution is performed with a constant approximation of the degree of membership of X_j to the i-th cluster and the determination of the centroid of the i-th cluster according to the following equations (Eq. 2, Eq. 3):

$$u_{ij} = \frac{\left(\dfrac{1}{d^2(X_j,V_i)}\right)^{\frac{1}{(q-1)}}}{\sum_{k=1}^{K}\left(\dfrac{1}{d^2(X_j,V_i)}\right)^{\frac{1}{(q-1)}}} \tag{2}$$

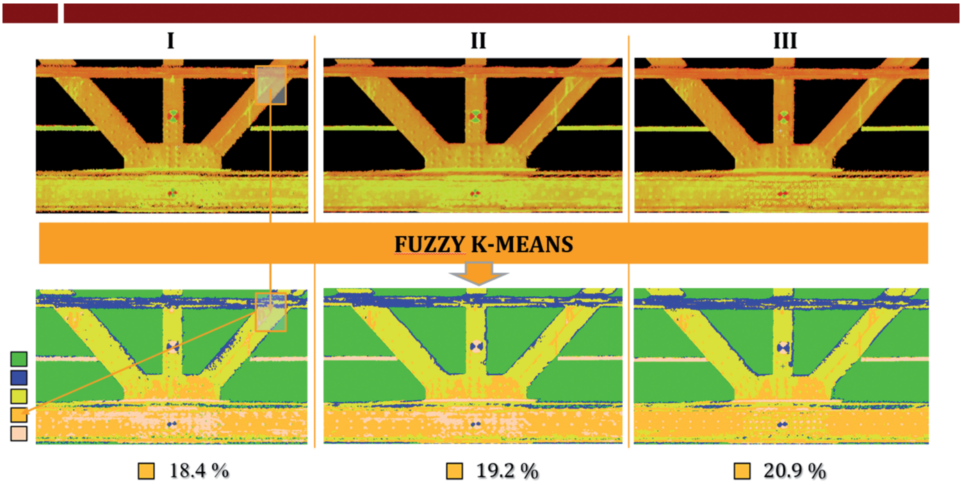
$$\widehat{V}_{\iota} = \frac{\sum_{j=1}^{N}(u_{ij})^{q}X_{j}}{\sum_{j=1}^{N}(u_{ij})^{q}} \tag{3}$$

The iteration process stops when the termination criterion ε reaches a value between (0,1) [Sánchez-Aparicio et al. 2018]. The conditional solution of the function (Eq. 1) in the Fuzzy K-Means algorithm translates into particularly good classification results for pixels located between cluster centres [Mitka et al. 2016].

Point clouds captured with the same laser scanner were extracted for the selected test field, representing the object in a non-damped state. From the scan data, orthoplans were generated on the reflectance beam intensity scale for the test field in series I, II and III. Unsupervised classification was performed in CATALYST Professional using the Fuzzy K-Means algorithm.

3. Results and discussion

Unsupervised classification of the rasters of the monochrome fragment of the bridge surface with the Fuzzy K-Means algorithm was performed in a 11 iterations using 5 pixel clusters. Image rasters in the intensity of the reflectance beam were classified. The number of 5 pixel clusters was determined empirically, by successive trials classifying pixels into an increasingly smaller number of classes and so that the corresponding clusters represent surface coverages with the same physical characteristics. The results of the classification are shown in Figure 7.



Source: Author's own study

Fig. 7. Fuzzy K-Means classification results for test fields of a monochromatic steel railway bridge in measurement series I, II, III

The images of the test field after classification into 5 pixel clusters were confronted with the photographic documentation, establishing cluster no. 4 as representing surface corrosion. With the information on its volume, the percentage of corroded surfaces in the area of the test field was determined in successive measurement series (Fig. 7). This percentage represented the proportion of pixels classified in cluster 4 (corrosion) in relation to the total number of pixels in the test field.

In addition to the corrosion percentage, the results of the classification of the test field images made it possible to establish an average annual corrosion rate of 1.25%. It can therefore be concluded that, in an average sense, an area of 1 m^2 will corrode in the course of a year over an area of 11 cm square.

The carried out procedure for surface corrosion detection is part of a trend of scientific studies dedicated to non-destructive methods of identifying damage to steel objects. Similar results were demonstrated by [Jin et al. 2021], who created a synergy between video and infrared images. In their study, they additionally performed subsurface corrosion detection, which poses an open scientific challenge to the approach presented in this paper. Meanwhile, Munawar et al. [2022] carried out automatic corrosion detection of bridge infrastructure based on machine learning in the analysis of images captured by unmanned aerial vehicles. They too aimed to detect deep corrosion and successfully identified this type of surface damage.

4. Conclusions

Scientific work on the detection of the corroded surface of a railway bridge from TLS data, which has been studied for its stability in the past, has led to the following conclusions.

- The method of classifying an unsupervised raster representation of reflectance intensity (generated from TLS data), similarly to classical remote sensing, produces classes of pixels with similar reflectance properties.
- The intensity of the object's point cloud, as the fourth coordinate, through the use of unsupervised classification tools ensures the detection of changes in the surface properties of the monochromatic railway bridge.
- Thanks to differentiation of imaging it is possible to identify changes in:
  - location and extent of corrosion,
  - the rate of their development in case of old steel structures,
  - the detection of cracks and fissures as structure's hot spots,

  indicating that the operational capacity of the structure is coming to an end, as forseen in the technical documentation.

The notion of assessing the surface corrosion of a steel railway bridge using laser scanning data provides a promising basis and foreshadows scientific work on defining the procedure for surface corrosion detection from data acquired with different sensors.

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