Automation in Construction 72 (2016) 258–268

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Automated processing of large point clouds for structural health monitoring of masonry arch bridges

B. Riveiro [a,*], M.J. DeJong [b], B. Conde [a]

[a] Department of Materials Engineering, Applied Mechanics and Construction, School of Industrial Engineering, University of Vigo, C.P., Vigo 36208, Spain
[b] Department of Engineering, University of Cambridge, CB2 1PZ, Cambridge, United Kingdom

ARTICLE INFO

Article history:
Accepted 29 February 2016
Available online 13 March 2016

Keywords:
LiDAR
Point clouds
Automatic processing
Masonry arch bridges

ABSTRACT

Laser scanning technology is gaining popularity in a wide range of applications due to the increasing accuracy and speed at which data can be collected and an increase in laser scan data processing tools. Nevertheless, manual operations for specific applications are time consuming and can require high-performance computers to produce suitable models for further operations. Thus, laser scan data are underused in the civil engineering community. New procedures that automate the data processing for specific but repetitive infrastructure typologies are required to make full use of the technology as a basic tool for infrastructure assessment and asset management. This paper presents a new method for fully automated point cloud segmentation of masonry arch bridges. The method efficiently creates segmented, spatially related and organized point clouds, which each contain the relevant geometric data for a particular component (pier, arch, spandrel wall, etc.) of the structure. The segmentation is based in the combination of a heuristic approach and image processing tools adapted to voxel structures. The proposed methodology provides the essential processed data required for structural health monitoring of masonry arch bridges based on geometric anomalies. The method was validated using a representative sample of masonry arch bridges. The results demonstrate that this tool can provide data for further structural operations without requiring neither training in laser scanning technology nor high-performance computers for such data processing.

1. Introduction

Geomatic technologies continue to gain popularity for geometric characterization. Three main advantages of these technologies are their non-destructive nature, their ability to capture a wide variety of visual and spatial data very quickly, and their potential for use in a wide variety of fields. In civil engineering, these technologies have been used in several ways, including creating geometric 3D models that can be used for the creation of accurate updated drawings, providing the geometric basis for subsequent structural analysis and contributing to the objective quantification of structural damage.

Laser scanning is one of the remote sensing technologies that have significantly evolved in recent years. The literature shows a large number of applications in civil engineering where the technology suits the requirements for detailed documentation (inventory and inspection) of large infrastructure (roads, railways, bridges, ports, etc.). The main reason for the extensive adoption of laser scanning instead of traditional routine procedures is the huge amount of accurate data that can be collected. The data include not only geometry but also different radiometric attributes. Moreover, the value of data for common inventory and inspection activities means that the data are being collected increasingly often. These aspects, together with the increasing density of scan data, have created a big-data problem that cannot be handled by traditional data management systems in terms of storage, processing and interpretation.

Thus, despite the tremendous advantages of the technology, there are important limitations preventing more widespread implementation in civil engineering. The principal limitation is the time and training required to manually process the huge quantity of data that point clouds contain. In fact, despite the above stated advantages of providing extensive and accurate information to perform structural assessment and health monitoring, many people are resistant to the technology due to the processing times involved. New methods that can automatically process LiDAR data and subsequently provide an automatic and organized interpretation are required.

Many authors have proposed semi-automatic or automatic methods to allow application of laser scan data to several fields of engineering. Laefer et al. [6]) used terrestrial laser scanning as a method to collect data for automatic crack detection in building façades. Olsen et al. [11]) proposed on the use of laser scanning for damage assessment, including methods to perform damage detection and volumetric change analysis. Truong-Hong et al. [20]) proposed a method to automatically process point clouds and derive CAD models suitable for subsequent

* Corresponding author. Tel.: +34 986 813 661; fax: +34 986 811 924.
E-mail address: belenriveiro@uvigo.es (B. Riveiro).

http://dx.doi.org/10.1016/j.autcon.2016.02.009
0926-5805/

structural computations. For the particular case of masonry structures, methods have been proposed for the individual modelling of stones ([15]; McInerney et al. [9]). Note that these applications are relatively specific, focusing the point cloud processing objectives enough to make an automation procedure feasible, but still general and repeatable enough to warrant the development of the automation process.

Meanwhile, masonry arch bridges are of great importance in transport networks (roads and rail), with particular relevance in Europe. According to Orbán [12]), Europe has more than 200,000 masonry arch bridges in service, representing approximately 60% of the total bridge stock. More than 70% of these bridges date from the 19th century and approximately 12% are older than 150 years (some dating from Mediaeval times or even from the Roman period). Thus, this huge infrastructure stock is in continual need of assessment and maintenance to support the transport network, but also has an incalculable heritage value.

In many cases, masonry arch bridges have been subjected to a significant increase in the loading for which they were designed. The effect of different loading (static, dynamic, cyclic) together with other effects (environmental degradation, settlement, change of use, extension, etc.) can provoke changes of geometry over time. It is well known that the geometry of this typology of bridge is a key factor in terms of their load carrying capacity [3,5,7]. However, the geometric changes mention above can also greatly influence the dynamic response and rate of degradation of the bridge, and therefore its serviceability. Many of the problems of these bridges cannot be properly understood without an understanding of geometric deformations. However, the signs of structural problems may be manifested by subtle geometric changes, so accurate and detailed geometric characterization is required to provide a proper diagnosis.

Several monitoring methodologies are used to assess masonry bridges, including measuring crack openings and acceleration. However, these methods must be used in combination with geometric surveying to understand global behavior, as mentioned above. Traditional surveying is typically applied to obtain detailed geometry [1,10]. Photogrammetry and laser scanning [14,17] have proved useful for detailed geometric documentation of arch bridges, but also to provide suitable models for subsequent structural analysis. In particular, laser scan data provides the detail required to detect geometric anomalies [13], but automated processes for this purpose have yet to be developed.

In this paper, a new method for fully automated point cloud segmentation of masonry arch bridges is proposed. The objective of the automated method is to efficiently create segmented, spatially related and organized point clouds. These segmented point clouds provide the essential data required for structural health monitoring based on geometric anomalies. Moreover, this research aims to provide a method to easily handle large point clouds and provide civil engineers with processed data for further structural operations without requiring training in laser scanning technology or high-performance computers for data processing. The detailed methodology is explained in Section 2, and the results obtained for a set of masonry arch bridges in Spain are presented in Section 3. Finally, conclusion and suggestions for future research are given in Section 4.

2. Methodology

The proposed method uses 3D point cloud data and topological characteristics of masonry arch bridges to enable automation. The method starts with a registered point cloud of a bridge as input. This input data format was selected because the objective is to provide a tool for construction and structural engineers. Also, a registered point cloud is the most primitive product delivered by laser scanning surveyors. The supplied point cloud is often dense and comprised of a large number of 3D coordinates that are redundant. Therefore, the first step is to 3D filter the data using voxelization. The resulting optimized and reduced point cloud has the advantage of being easier to process, so it will be used as the primitive point cloud from which the different elements will be segmented. At the end of the process, the filtered and segmented point clouds can be used to segment the points from the original dense point cloud, if desired prior to further analysis by the engineer.

The segmentation of the global point cloud in its composing elements is made combining a heuristic method for vertical wall segmentation, with image processing tools, adapted to three dimensions, for the non-vertical walls of the bridge. Topological constraints are then used to define the order and spatial relation of the bridge elements, and to store the independent element point clouds coherently in a database. Fig. 1 shows the general workflow of the developed methodology, the steps of which are described further in the following subsections.

2.1. Point cloud reduction and computation of normals

To reduce the original point cloud, a 3D filter is applied. The filter uses an image processing voxelization approach adapted to 3D space [20]. It takes advantage of geometric information provided by the laser scanning data. Working with a downsampled point cloud permits the segmentation operations to be performed without high computing resources. Additionally, the downsampled point cloud eliminates redundant and noisy data and may be sufficient when the level of detail of the original laser scan exceeds the geometrical inventory and/or inspection requirements. In cases where the full resolution of the original point cloud is needed for further processing, the proposed method uses the segmentation results for the reduced point cloud as a pattern to partition the original point cloud.

Before applying the voxelization filter to the point cloud, the user is prompted to specify the desired voxel size, which might vary depending on the initial resolution of the data. However, this step can be avoided if the point cloud is to be processed with the original resolution. For the validation of the method presented in this paper, a voxel size of 10 cm was used.

On the other hand, all the parameters used for the method (thresholds, neighborhood, etc.) are computed adaptively depending on the point cloud characteristics (mainly density and object size). Additionally, some of them can be also fixed by the user attending to previous knowledge of the structure.

After having downsampled the point cloud, the point normals are computed in order to extract information about the type of surface on which each point is contained. For that purpose, principal component analysis (PCA) [4] was used. This method not only provides the normal direction of each point using a set of points in close proximity, but also provides information about the dimensionality (1D, 2D or 3D) of each point based on the eigenvalues of the covariance matrix [4]. To minimize noise effects during the subsequent segmentation operations, only points classified as 2D features were selected for subsequent segmentation.

The point normals, computed as the third eigenvector of the covariance matrix, provide key information for the segmentation process. The normal vectors were initially obtained in Cartesian coordinates but were then converted to spherical coordinate system. The elevation angle and the azimuth of each point normal were then used, along with knowledge of the morphologic configuration of masonry arch bridges, for the classification of points.

The points were first classified based on their elevation angle. For the case of masonry arch bridges, vertical spandrel walls provide valuable topologic information, and consequently, it is useful to identify them first. Unfortunately, classification of points by their elevation angle alone cannot identify spandrel walls since other vertical elements are also present (piers, cutwaters, etc). In any case, an initial classification based on elevation is performed in order to distinguish two main groups of elements: vertical walls (spandrel walls, piers, cutwaters, abutments, etc.) and non-vertical walls (arches, pathway (i.e., road surface), cutwater hats, etc.).