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Development of a novel open tool for the segmentation of 3D point clouds of masonry walls

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Abstract

Traditional visual fabric surveying has been shown to lack accuracy and objectivity, and be characterised by limited interoperability, with other methods significantly reducing productivity and hindering efficiency. Moving beyond established visual survey methods, the rapid evolution of reality capture technologies used for digital documentation, such as terrestrial laser scanning, is facilitating the acquisition of precise geometric and colour-related data that can more effectively support surveying, maintenance and repair works. Reality capture data of this nature is subsequently processed, delivering meaningful information about individual masonry units that can be integrated into progressive building maintenance management systems (e.g. BIM-based). The present paper outlines the structure of an innovative tool for the semi-automated segmentation of 3D point clouds of rubble-constructed stone walls into individual masonry units and mortar regions. This tool has been developed as a plugin for the open source 3D data processing software 'CloudCompare'. An algorithm based on the Continuous Wavelet Transform is employed for the automatic segmentation of the point cloud and shows high levels of accuracy. A manual segmentation functionality is also added to the tool to correct any error from the initial automated segmentation. The proposed tool has been tested and validated with 3D data from several walls of Linlithgow Palace, a historic building of national importance managed and maintained by Historic Environment Scotland (HES). The results are positive and demonstrate the ease of use and functionality of the tool in attaining better and faster survey outcomes.

Introduction

Internationally, a large proportion of buildings and infrastructure are constructed in masonry (e.g. from churches and castles to traditional pre-1919 housing stock and historic infrastructure). Maintaining these structures is critical from a safety perspective but also for sustaining their utility and the economic benefits that flow from this. Contextualising this, it is estimated that there are 0.5 million pre-1919 traditional (i.e. historic) buildings in Scotland (HES, 2018), these being ostensibly constructed in lime-based materials. Repair and maintenance expenditure for the historic built environment can therefore result in costs amounting to £1.47 billion per year (SQW, 2017) (Ecorys, 2012).

Frequent and objective surveying of masonry structures is fundamental to their effective maintenance. Yet, determination of the geometry and material characteristics associated with the structures analysed have been historically approximated, reflecting the limitations of traditional surveying and recording methods. Modern reality capture technologies, such as terrestrial laser scanning (TLS) and photogrammetry/structure from motion (PG/SfM), have enabled structural engineers to develop numerical models that more faithfully reflect the surface geometry of structures, with clear benefits to the quality of the results (Riveiro et al., 2016). However, while these technologies are beneficial for the recording of the *as-is* state of structures (Wilson et al., 2013), their interpretation to create 2D architectural line drawings requires a manual undertaking that is slow and subjective (Forster and Douglas, 2010). There is thus a need to develop effective automated solutions to further accelerate structural assessments that are more rigourous in terms of their inputs. A critical step in achieving this is the segmentation of the captured *as-is* data into the structure's constitutive elements: the individual stones and the mortar regions.

The authors of this paper have developed an automated masonry segmentation approach (Valero et al. 2018a) and tested and validated it in a variety of masonry walls that are representative of much of the world's masonry (Valero et al. 2018a; Valero et al. 2018b). In this paper, the authors present a novel tool that implements that algorithm for rubble-constructed masonry walls along with complementary functionalities in a software package aimed to be made available to the surveying, architectural and enginnering community for wide use. More specifically, these functionalities have been implemented as a plugin for the free open-source 3D data processing software CloudCompare (CC) (CloudCompare, 2019). This software is being increasingly used by the heritage community. For example, Yordanov et al. (2019) use CC to calculate cloud-to-cloud distances in heritage sites; Blaszczak-Bak et al. (2018) subsample point clouds of virtualised stones; and Koehl et al. (2019) use CC for aligning point clouds and subsequent meshing-related operations.

The rest of the paper is structured as follows: first, the developed tool is introduced; experimental results are subsequently presented, covering perfomance and usability; and finally, conclusions and future works are discussed.

The tool

Aiming to provide a tool for the segmentation of digitised masonry walls into individual stones and mortar regions, as shown in Figure 1, the authors have developed two plugins for CC. The first plugin runs an automatic process for the segmentation of walls into stones and mortar, whereas the second one supports a manual segmentation process , that can be used for a completely manual segmentation or to refine the output from a previous automatic segmentation. In both automatic and manual segmentations, CC source code, in C++ language, has been used as a base, including additional libraries from OpenCV (Bradski, 2000) for image processing (i.e. CWT) and PCL (Rusu, 2011) for fast and efficient point cloud handling.

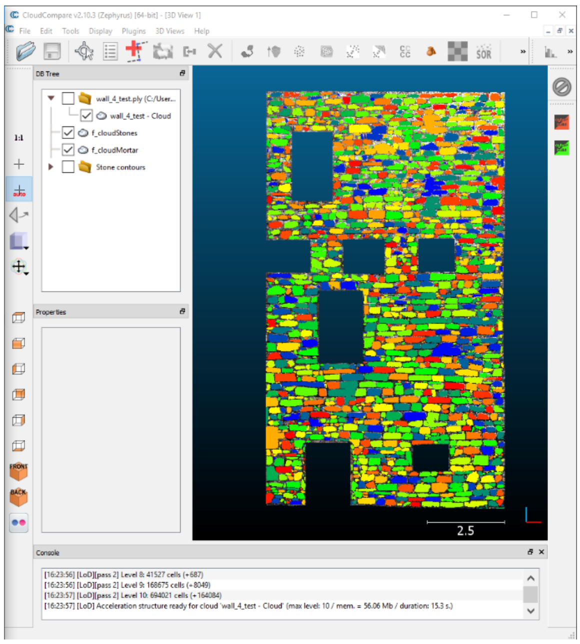

Figure 1 CloudCompare window showing segmentation results

Automatic Segmentation Plugin (ASP) The objective of the Automatic Segmentation Plugin (ASP) is to automatically label stones and mortar within a masonry wall, segmenting and saving the outcomes as distinct entities that can be later exploited independently. This plugin is grounded on an algorithm that uses the Continous Wavelet Transform (CWT) to identify mortar regions on rubble masonry walls (Valero et al., 2018). The flowchart in Figure 2 illustrates the more relevant operations performed during the execution of the ASP

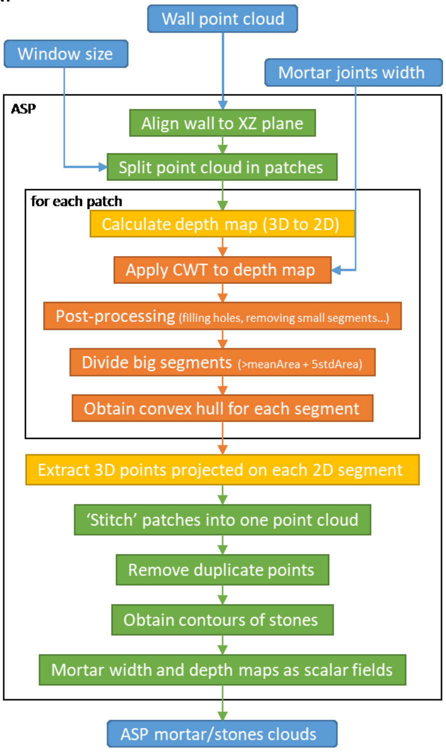

Figure 2 Overview of the proposed pipeline for the automatic segmentation of masonry walls. Boxes in blue represent input and output data; green boxes are operations performed on point clouds; yellow represents 2D-3D data conversion and orange is used for image processing tasks

First, a point cloud corresponding to a digitised masonry wall is loaded into CC and, then, the ASP is triggered after clicking on the plugin icon. A dialogue window asks the user for two parameters: an estimate value for the width of mortar joints; and a *window* (i.e. rectangle) size to divide the wall in rectangular patches (see Figure 3). These patches facilitate a local analysis of the wall by means of the CWT and, additionally, deal with potential memory management issues.

For each patch, 3D data is converted to 2.5D (i.e. depth map), by projecting all the points into a plane parallel to XZ. After this operation, the CWT is calculated for the depth map and some post-processing tasks are subsequently performed,e.g. filling holes, removing small segments. Finally, a convex hull is calculated for each segment.

Once the final 2D segments are obtained, stone labelling in the 2.5D image is mapped back to the 3D point cloud and the patches are stitched together (see Figure 4), duplicate points are removed and the contours of the stones are calculated as polylines. Finally, *stones cloud* and *mortar cloud* are produced and mortar width and mortar depth are calculated.

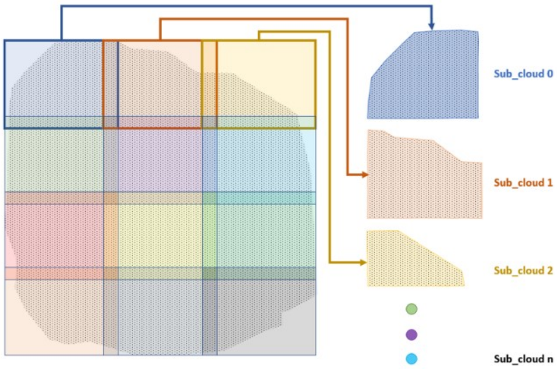

Figure 3 Strategy followed to divide the wall in a set of adjacent point clouds.

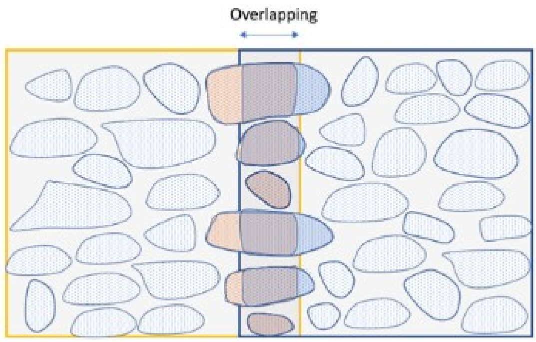

Figure 4 Schematic representation of the overlapping between segments (i.e. stones) for two neighbouring sub clouds.

Manual Segmentation Plugin (MSP) The Manual Segmentation Plugin (MSP) is executed if the results obtained after running the ASP need to be refined. Additionally, the MSP plugin can be used when a completely manual segmentation of the wall is required. The process followed in this case is summarised in Figure 5. Note that red arrows are used for operations related to the refinement of previously segmented point clouds.

As illustrated, the original point cloud is required, together with the *stones cloud* obtained by means of the ASP, if further refinement is sought. Next, polylines delimiting the boundaries of stones, to be newly created or modified, can be drawn by the user. For each polyline, all the 3D points enclosed by the polygon are evaluated: if these are not already in the *stones cloud*, they are added and labelled as a new stone; if the points were previously labelled as part of another stone, these are relabelled (see Figure 6). After evaluating all the polylines, the remaining points (i.e. not labelled as stone) are labelled as mortar and the mortar cloud is created or updated.

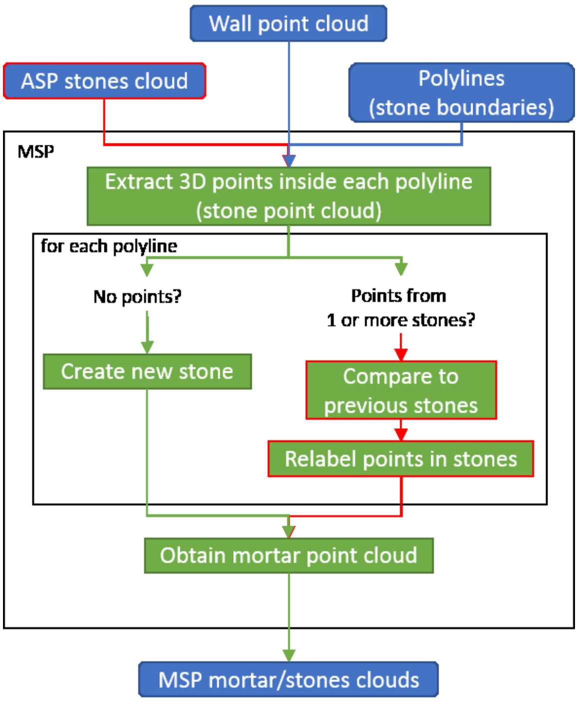

Figure 5 Overview of the proposed pipeline for the manual segmentation of masonry walls. Boxes in blue represent input and output data; boxes with red outline correspond to the operations linked to the manual correction of previously existing [automatic] segmentation

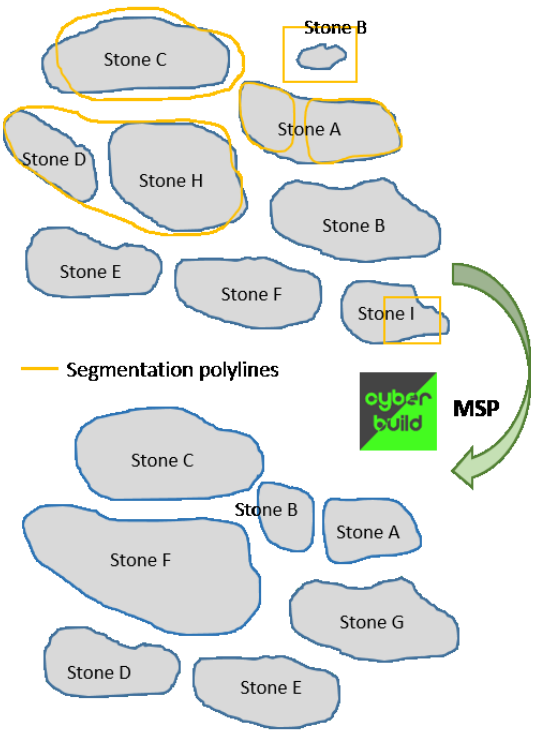

Figure 6 2D representation of the manual correction of automatically segmented stones. Yellow polylines represent the new boundaries. Note that rectangular polylines (e.g. stones B and I) are used to remove incorrectly labelled stones (i.e. false positives).

Experimental results

To test the developed tool and evaluate its performance and usability, a series of experiments have been carried out.

The performance of the ASP has been tested with data from the west façade of the interior courtyard of Linlithgow Palace, Scotland, a medieval (1424-1624) category A listed building and Scheduled Ancient Monument. As highlighted in yellow in Figure 7, a region of more than 100 m^2 was selected as input. For this first experiment, a desktop Alienware (Intel i7-3.60GHz, 16GB RAM) has been used.

Figure 7 Linlithgow Palace cortyard west wall. Region used for ASP tests is highlighted in yellow

Before running the segmentation process, an average mortar joint width of 4 cm has been selected after a visual inspection of the site, and different window sizes have been tested for segmentation, obtaining the results summarised in Table 1.

Table 1 Results obtained for different sizes of windows with a mortar joint width of 4cm.

Window size [m]	**Number of patches**	**Points per patch [MPts]**	**Overall segmentation time [s]**
0.75 x 0.5	299	0.25	480
1.5 x 1	84	1	300
1.5 x 1.5	60	1.5	280
3 x 2	21	3.5	260
4.5 x 3	10	6.3	280
6 x 4	8	8	300

Overall segmentation times reported in Table 1 show that a balance must be struck between the size of the patches and the size of their overlap.

With small windows, processing of individual patches is quick but overall stitching requires more time. For large windows, processing of individual patches is slower but overall stitching is faster. A good balance is achieved for the window size 3x2m.
To test the usability of the tool and evaluate the quality of the output delivered by the ASP and MSP, 10 professionals working in architectural conservation were invited to participate in a trial session, among which 8 had previous experience in working with point clouds and 6 of these had previously worked with CC.
These test subjects completed two exercises: first, they manually segmented a part of a wall, sized 2x2m, using the MSP alone; and second, they ran the ASP for a different region with dimensions 3x2m and corrected the obtained results with the MSP.
For each wall section, one segmentation was chosen as ground truth which was produced by an archaeologist expert in the segmentation of digitised 2D masonry walls. The segmented (stone) point clouds produced by the other professionals were then compared to these ones. Table 2 summarises the results. The first row reports the average, for all the test subjects, of the percentage of points correctly labelled as stone in the point cloud. The second row gives the average distance from mislabelled points (i.e. false positives) to the closest stone. Regarding time spent in the processes, the third row present information about the time spent by test subjects. And, as the dimensions of the patches were different, time values were divided by the area of each patch (fourth line) to establish a fairer comparison between MSP and ASP+MSP. The percentage of stone area properly labelled as stone is high in both MSP and ASP+MSP cases, with marginally better results for ASP+MSP. The average distance from mislabelled points to their closest stone was also similar in both cases. Given this comparable quality performance, the time performance shows that the users are almost four times faster when using ASP+MSP. This demonstrates the value of the algorithm we developed for the ASP. Note that the automatic segmentation of the wall typically takes just a few seconds for patches of those dimensions.

Table 2 Results obtained for manual segmentation and correction after automatic segmentation

	MSP	ASP + MSP
Average (avg) correct labels [%]	95.0	97.3
Avg distance of mislabeled [cm]	1.95	1.94
Avg time [min]	34.5	14.5
Avg time [min/m^2]	8.6	2.4

Conclusions and future works

This paper presented an innovative tool, developed as a CC plugin, to help conservation professionals produce more objective evaluations of rubble masonry before maintenance tasks are performed. While the automated process shows to be effective, the ability to interact with the results from the automatic segmentation and refine them is critical for the accuracy of the outcome, which will be utilised for many sucessive tasks that flow from this first order operation. Note that resulting segmentation (using the developed tool) should be undertaken once only, as the output stone contours can be used to segment future digital documentation epochs of the walls.

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