Historic Digital Survey: Reality Capture and Automatic Data Processing for the Interpretation and Analysis of Historic Architectural Rubble Masonry

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Abstract. Detailed segmentation for the analysis of rubble masonry substrates is complex due to the lack of uniformity in size, geometry, coursing, bonding, and materials composition and texture of the individual stones. State-of-the-art technologies, such as Terrestrial Laser Scanning (TLS) or photogrammetry, deliver precise geometrical and coloured data that can be processed by means of innovative techniques to segment and label these masonry units. The automatic segmentation of individual stones supports further analysis of rubble masonry via several parameters related to their geometry and face colour. These can be utilised for deciphering architectural construction methods and changes in materials, as well as being employed for practical maintenance and repair operations. This paper presents a new strategy for investigating historic masonry substrates, especially from the perspective of data processing methods supporting the automated segmentation and labelling of rubble stone walls. In particular, an innovative method based on the Continuous Wavelet Transform (CWT) is proposed for the automatic segmentation of rubble stone walls, which subsequently enables the automated analysis of the individual stones and mortar regions. Different experiments have been conducted on two significant Cultural Heritage (CH) buildings in Scotland, with the results clearly demonstrating the potential of the proposed method for historic interpretation and analysis.

Keywords: data processing, reality capture, masonry surveying, stone, historic interpretation and analysis

1 Introduction

Survey of masonry substrates is undertaken for many reasons. Primary objectives can include survey for condition, maintenance, measurement and costing and importantly for architectural interpretation [1] and historic analysis [2]. Traditional visual survey and documentation for the detailed analysis of historic rubble substrates is commonly constrained by difficulties in access and working at height, and can be time consuming and costly. Traditional methods also present inherent technical difficulties, due to a **lack** of uniformity in masonry size, variation in coursing and bonding, complexity of shape and geometry, materials composition, geological variance, colour and texture, and the sheer volume of the units exhibited. As a result, segmentation of individual rubble stone would rarely be attempted beyond establishing a broad sense of masonry building style within a localised region supported through narrative descriptions and crude m^2 approximations.

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Masonry can be critical in deciphering architectural evolution, and fabric change is an essential mechanism for the determination of ‘cultural significance’ [3]. Indeed, ‘cultural significance’ is inherently important, underpinning the majority of technical conservation and repair operations enabling strategic prioritisation of limited financial resources for maintenance and repair. Change associated with adaptation and fabric repair are often manifest in their materials. Specific, highly contextualised information associated with the masonry build style, coursing, bonding, stone to mortar ratio, dressing and tooling are prominent features that produce historic construction value. Beyond the technical and structural factors, this yields fundamental information relating to historic socio-economic and socio-technical processes. Indeed, variation of stone materials, its durability, quality and aesthetics reflect the availability and regional sourcing versus the cost of transportation [4].

Reflecting on previous literature, recent advances in remote sensing technologies (e.g. Terrestrial Laser Scanning (TLS) and photogrammetry) and their increasing use in the Architecture, Engineering and Construction (AEC) industry offer the promise of enhanced survey accuracy with the logical benefits that flow from primary characteristics such as cost, safety, objectivity and more specifically for this project analysis and interpretation. Global scale projects (e.g. Scottish Ten [5]) for Cultural Heritage (CH) have been oriented toward the digitisation of historical buildings ostensibly for documentation and recording purposes. Regarding the processing of these acquired data to deliver pragmatic meaningful information, a semi-automatic delineation and masonry classification was developed by Oses and Dornaika [6] who used Artificial Intelligence techniques (k-NN classifiers) to identify stone blocks in 2D images. Additionally, Cappellini et al. [7] proposed a semi-automatic approach to semantically label 2.5D data (colour and depth information) of brick and stone walls obtained using photogrammetry.

In this paper, a new strategy for investigating historic masonry substrates is presented. Several algorithms, based on computer vision tools, have been developed to process digitised façades of CH buildings made of rubble stone, and deliver information useful for maintenance and repair works, as well as interpretation tasks and further analysis.

The remaining sections of the document are structured as follows: Section 2 summarises the method designed for stone/mortar segmentation. Section 3 presents the parameters extracted from the segmented stones. Section 4 illustrates the experiments undertaken to test the developed techniques for interpretation and reports the obtained results. Finally, Section 5 concludes offering direction for future works.

2 Stone segmentation and labelling

The proposed method uses 3D coloured point cloud as its input, which is obtained via a TLS device, as the example shown in **Figure 1** (a). The 3D data are initially projected onto a vertical plane, generating a 2.5D map (**Figure 1** (b)) with a regular sampling δ_p. Subsequently, a 2D Continuous Wavelet Transform (CWT) is applied to the depth map, outputting a scalogram that shows the CWT response in each pixel of the depth map for the characteristic frequency (*f*). Frequency *f* is proportional to the scale *a*, that can be set by the user as the estimate of the typical width of the mortar joints for such wall section [8]. The outputted angular values of the 2D CWT coefficients are shown in **Figure 1** (c). As can be seen in that figure, this stage delivers an approximate segmentation of the individual stones and mortar regions.

However, due to the irregularity of the surface of the stones, some areas inside the stone segments are also labelled as mortar. To correct this, a convexity operator (i.e. convex hull) is applied to each stone segment. The result of this operation is illustrated in **Figure 1 (**d).

An iterative dilation process is then applied using colour information to refine the boundaries of the segments. **Figure 1** (e) shows the final shapes of the segmented stones. The last stage in the process is mapping the segmentation results back to the 3D point cloud (**Figure 1** (f)).

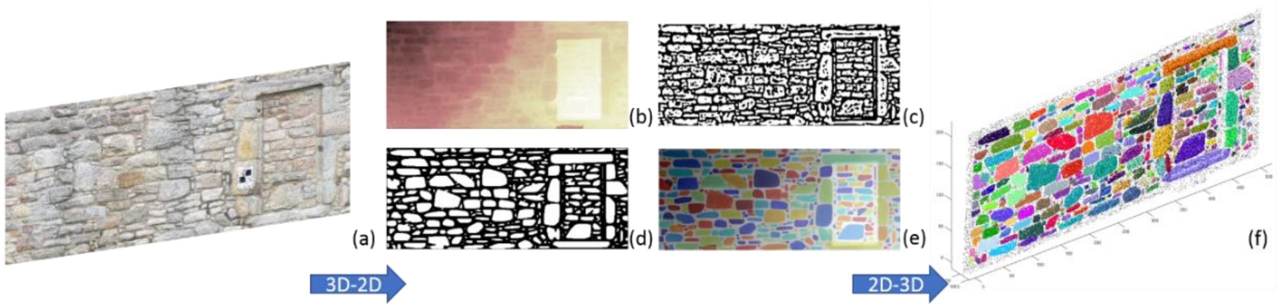


Figure 1. Summary of the rubble stone segmentation process. a) Input wall 3D point cloud, b) depth map, c) 2D CWT scalogram for the selected scale a, d) 2D stone segments after convex hull step, e) 2D stone segments after the final dilation step; and f) final segmentation re-mapped onto the 3D point cloud.

3 Parameters extraction

After segmenting the stones using the method summarised in the previous section, the data subsets corresponding to individual stones are analysed to obtain several parameters that can be used for further classification and interpretation works. These parameters are mainly based on the geometry of stones (contour and profile of the stone face), and on the colour of the point cloud.

3.1 Stone face contour

For each stone, the 3D point cloud is projected orthogonally onto a vertical plane, and discretised in a 2.5D map (1cm gridded) to facilitate further operations. For example, **Figure 1** shows a binary map obtained from a 2.5D map, where occupied pixels are coloured in white. This extent corresponds to the projected *area* of the stone. *Bounding box* is the smallest rectangle containing the stone region. ‘Area’ and ‘bounding box’ can then be used to compute the stone *rectangleness* (*R*), which is calculated as the fraction of the bounding box which is covered by the stone (Eq. (1)).

$$R = \frac{area}{bounding\_box} \quad \textbf{(1)}$$

The higher this parameter, the more rectangular the stone. In the case of rectangular stones (e.g. ashlar), *R* values are close to 1. This parameter can be used to identify regions of a wall covered by squared coursed rubble.

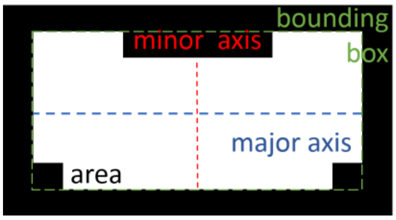


Figure 2. Parameters extracted from segmented stones.

The major (resp. minor) axis of the stone extent is defined as the length of the major (resp. minor) axis of the ellipse that has the same normalised second central moments as the area covered by the stone. The ratio of the lengths of the minor to major axes gives an indication of how 'oblong' a stone is and it is used for the calculation of *elongation* (E), as detailed in Eq. (2). Stones with similar minor and major axes (not oblong) have elongation values close to 0.

$$E = 1 - \frac{minor\_axis}{major\_axis} \tag{2}$$

Another parameter related to the shape of the stones is *roundness*. This metric, presented in Eq. (3), based on the idea presented by Cox [9] and called *circularity* (C), is the ratio of the area of the projection of the stone to the area of a circle with the same perimeter (p). Values of C close to 1 are associated with stones with circular faces.

$$C = \frac{4 \cdot area \cdot \pi}{p^2} \tag{3}$$

3.2 Stone face profile

The aforementioned metrics are related to the area and shape of the segmented stones. However, there are other geometric parameters that are useful to define and classify stones. For example, *roughness* (Ra) delivers information about the flatness of the stone's face profile (see Eq. (4)). After fitting a plane to a stone's 3D points, the distance between each point of the stone and this plane is used to calculate the roughness value as detailed in the following expression:

$$Ra = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(d_i - \mu)^2}\,, \text{ with } \mu = \frac{1}{N}\sum_{i=1}^{N} d_i \tag{4}$$

where N is the number of 3D points for the given stone face and d_i's are the projection distances of those points to the fitted plane.

3.3 Stone face colour

In addition to these parameters, RGB colour data obtained by the TLS for all 3D points can also be evaluated. First, the RGB colour data is converted into HSV format, using the algorithm presented in [10], and two metrics related to hue values (Eq. (5) and Eq. (6)) are used: H_v, which is the range of hue values in each stone; and H_σ, which is the standard deviation of hue values within each masonry unit.

$$H_r = \max(h_i) - \min(h_i) \quad \textbf{(5)}$$

$$H_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(h_i - \mu)^2}, \quad \mu = \frac{1}{N}\sum_{i=1}^{N} h_i \quad \textbf{(6)}$$

Finally, RGB colour data are converted to grayscale, by means of the approach presented by Anderson et al. [11], and the median value of g_i, the grayscale value of each point inside the stone face, is calculated for each stone, aiming to deliver information about the colour lightness of stones.

4 Experimental results

Thanks to the proposed automated approach for rubble stone wall segmentation, the calculation of the previously defined geometric parameters can easily be scaled up to whole building facades. This has significant advantages for contextualized architectural interpretation. This is especially true in the case of rubble masonry walls, in which stones are of a more pronounced shape, size and profile.

In this section, point clouds relating to the walls of two Scottish CH buildings; Craigmillar Castle and Linlithgow Palace were automatically segmented and stone maps were generated, enabling the analysis of different metrics. **Figure 1** shows the stone segmentation and labelling results. As can be clearly appreciated in **Figure 1** (b) and **Figure 1 (**c), Craigmillar wall is basically formed of uncoursed random rubble, meanwhile the façade of Linlithgow Palace (see **Figure 3** (c) and **Figure 3** (d)) is close to a coursed squared rubble wall.

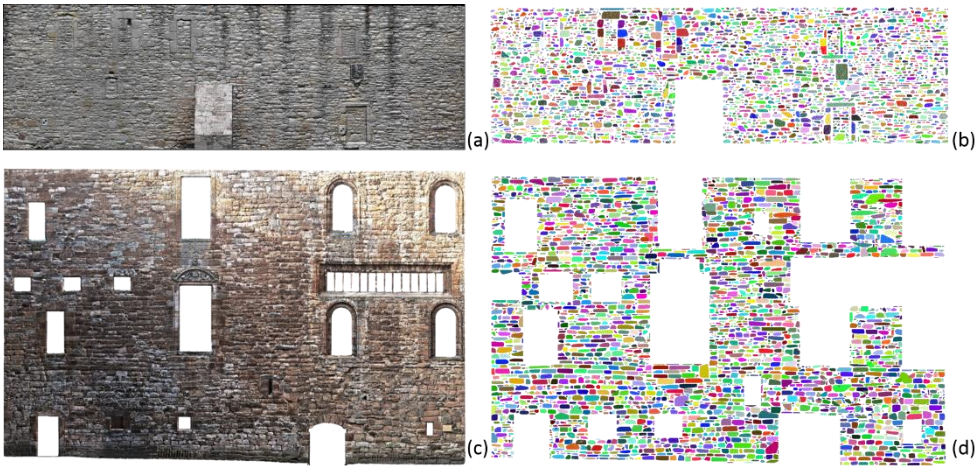


Figure 3. Walls segmentation results. Top row: Craigmillar Castle. a) 3D coloured point cloud, b) Segmented and labelled stones. Bottom row: Linlithgow Palace. c) 3D coloured point cloud, d) Segmented and labelled stones.

After segmenting and labelling the stones from these walls, the metrics presented in Section 3 are calculated for each segmented stone. The mean values of these parameters for both walls are presented in **Table 1**.

Table 1. Mean values for the proposed geometric parameters

	Linlithgow	Craigmillar
Elongation	0.56	0.51
Circularity	0.80	0.83
Rectangleness	0.81	0.85
Roughness [mm]	1.91	2.18
Area [cm2]	421.56	239.63

When evaluating the data in the table it is clear that stones at Linlithgow have a higher elongation value than Craigmillar, while the circularity parameter is larger in the façade of Craigmillar. The maps in **Figure 1** illustrate the elongation (**Figure 4** (a)) and circularity (**Figure 4** (b)) results for the two digitised walls. It is worth mentioning the dissimilarities in the map corresponding to circularity. While stones with a circularity coefficient close to 1 (i.e. almost circular in shape) are distributed around the wall of Cragmillar Castle, circular stones are concentrated principally at the bottom part of the façade in the case of Linlithgow. In addition, while the two maps show some level of correlation (elongated stones always have low circularity), they do not exactly provide the same information (non-elongated stones are not necessarily circular).

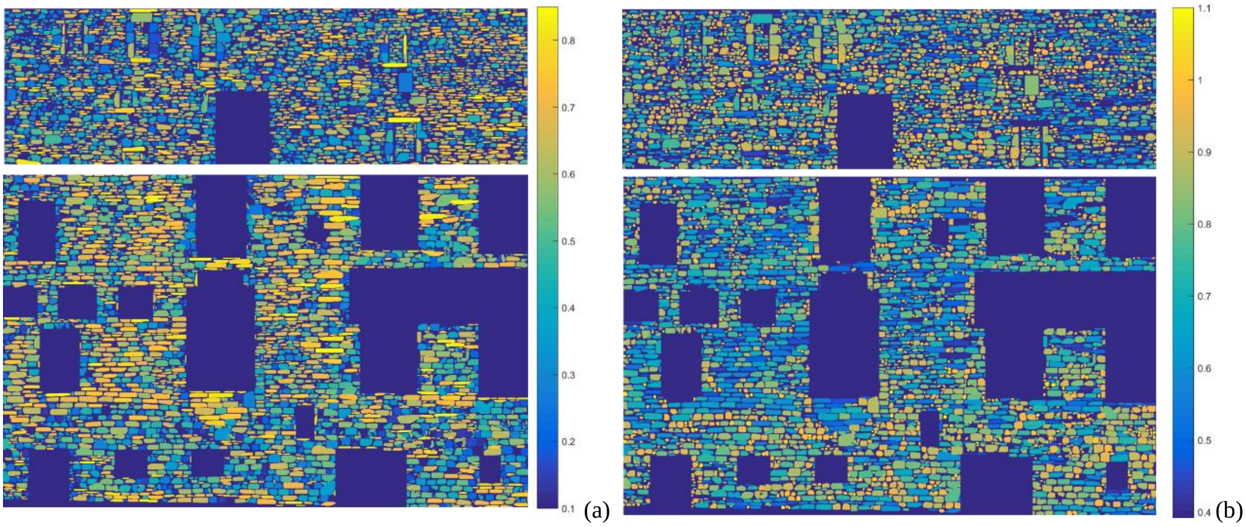
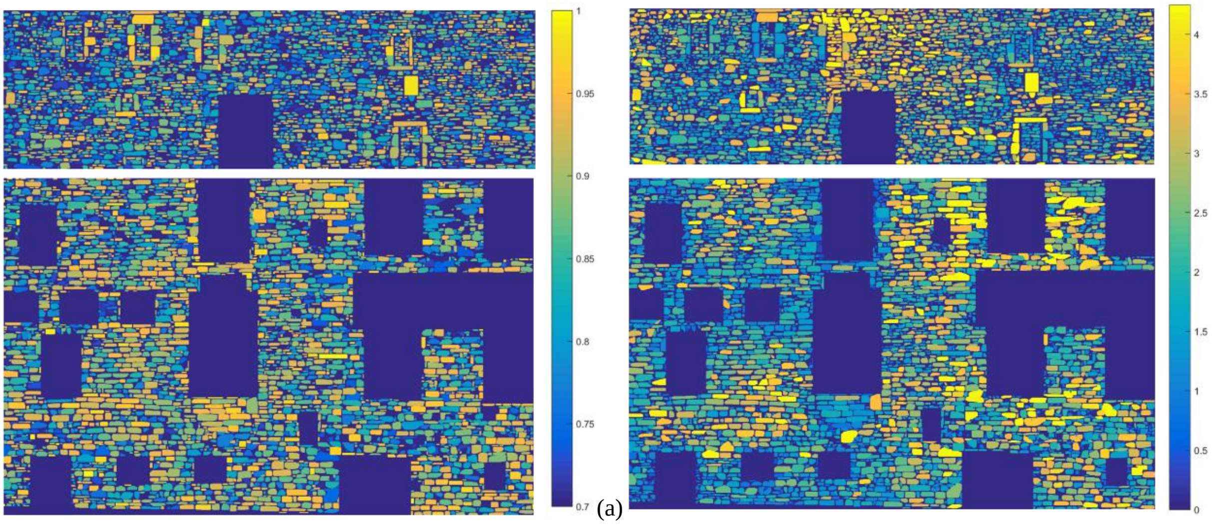


Figure 4. Stone maps for elongation (a) and circularity (b) coefficients

With respect to rectangleness, **Table 1** shows that the mean value is higher for Craigmillar Castle, and **Figure 1 (**a) shows the values of this coefficient for each individual stone. It is interesting to note that even though the mean value of rectangleness is higher for Craigmillar, the areas covered by yellow hues are larger in Linlithgow, due to the prevalence of squared coursed rubble. Finally, **Figure 1** (b) shows the roughness maps. According to the values in **Table 1** and as illustrated in the maps, the roughness is higher in the Craigmillar wall. In most cases, the stones highlighted in yellow in **Figure 1** (a) are coloured in blue hues in **Figure 1** (b), meaning that stones with higher values of rectangleness tend to have flatter profiles.

Information on rectangleness versus circularity is tangibly important for giving us an objective indication of socio-economic influences of construction. Analysis and interpretation would logically suggest that the greater rectangleness associated with the materials in Linlithgow Palace is attributed with stone reduction techniques tending to ashlar masonry production. Ashlar and squared coursed rubble are relative high cost masonry construction forms, associated with quality and importantly the prestigiousness of the walling. Conversely, the circularity of the masonry at Craigmillar castle suggests a less prestigious construction form (potentially defensive / flank wall) that may have acted as a relatively inferior substrate for a lime harl or render coats [12]. Additionally, the circular masonry may be associated with a geologically hard stone that is inherently difficult to dress into rectangular units within economic costs parameters.



(a) (b)

Figure 5. Stone maps for rectangleness (a) and roughness (b) coefficients. Roughness in mm.

Information obtained from the colour of the stones is employed to evaluate differences in the composition of masonry units and identify areas potentially affected by chromatic alterations. **Figure 1** (a) illustrates, for each stone, the median value of the grey. This grey component helps differentiate darker areas from brighter ones. In the top image of **Figure 1** (a), corresponding to Craigmillar, several vertically-orientated dark areas (i.e. blue in the figure) can be seen on the right hand of the top part of the façade. These areas are also noticeable in **Figure 1** (a) and are due to moisture and more specifically long-term surface water run-off. Regarding the results obtained from Linlithgow Palace wall, the incidence of light beams on the top part is detectable in the map, which is darker in the bottom part, where stones are affected by moisture.

Figure 1 (b) illustrates the standard deviation of the hue value for each stone. This parameter can be used to highlight discolouration. In the figure, stones coloured in yellow are those with a larger dispersion of hue, which can be a sign of colour-related defects, such as long-term ultra-violet light associated colour change and efflorescence. The left-hand side of Linlithgow's façade has stones with larger dispersion in hue, which is consistent with the manual observation of efflorescence in those areas.

5 Conclusions

This work presents innovative methods based on the automatic processing of TLS data, illustrating the potential of cutting-edge technologies and techniques for enhanced analysis of masonry construction, and more specifically rubble masonry construction. After the automated segmentation of stones in masonry walls, several geometric and colour-related parameters are automatically extracted that are of significance for interpretation and classification purposes. Various stone maps can then be generated to effectively support the analysis of the walls. The potential value of the proposed approach is demonstrated with two facades of two Scottish heritage buildings built in different periods. Future works will be oriented towards the evaluation of different kinds of masonry units, especially ashlar walls. Additionally, our work will focus on establishing automated methods to detect and classify decayed regions in stone walls.

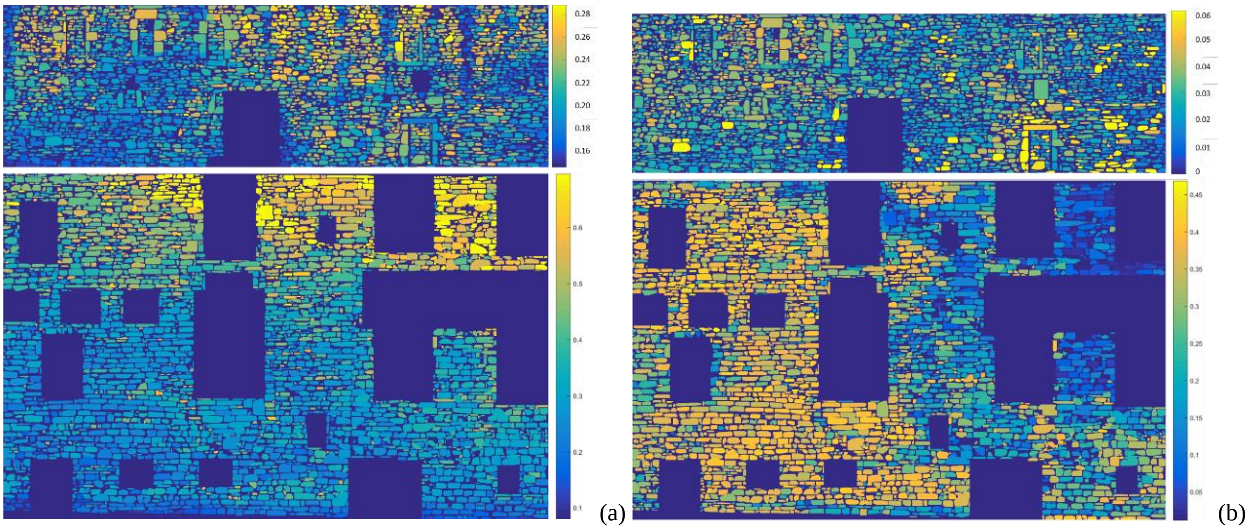


Figure 6. Stone maps for grayscale median values (a) and H_c coefficients (b).

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