Automation in Construction 96 (2018) 29–39

Contents lists available at ScienceDirect

Automation in Construction

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

Automatic segmentation of 3D point clouds of rubble masonry walls, and its application to building surveying, repair and maintenance

Enrique Valero, Frédéric Bosché*, Alan Forster

Institute for Sustainable Building Design, Heriot-Watt University, Edinburgh EH14 4AS, UK

ARTICLE INFO

Keywords:
Point cloud processing
Heritage science
Masonry
Stone
Surveying
Segmentation
Continuous wavelet transform

ABSTRACT

Changing climatic conditions are contributing to faster deterioration of building fabric. Increasing number of heavy rainfall events can particularly affect historic and Cultural Heritage (CH) buildings. These evolving and uncertain circumstances demand more frequent survey of building fabric to ensure satisfactory repair and maintenance. However, traditional fabric surveys have been shown to lack efficiency, accuracy and objectivity, hindering essential repair operations. The recent development of reality capture technologies, together with the development of algorithms to effectively process the acquired data, offers the promise of transformation of surveying methods.

This paper presents an original algorithm for automatic segmentation of individual masonry units and mortar regions in digitised rubble stone constructions, using geometrical and colour data acquired by Terrestrial Laser Scanning (TLS) devices. The algorithm is based on the 2D Continuous Wavelet Transform (CWT), and uniquely it does not require the wall to be flat or plumb. This characteristic is important because historic structures, in particular, commonly present non-negligible levels of bow, waviness and out-of-verticality.

The method is validated through experiments undertaken using data from two relevant and highly significant Scottish CH buildings. The value of such segmentation to building surveying and maintenance regimes is also further demonstrated with application in automated and accurate measurement of mortar recess and pinning. Overall, the results demonstrate the value of the automatic segmentation of masonry units towards more comprehensive and accurate surveys.

1. Introduction

One fifth of all buildings in Scotland are characterised as being historic. This includes more than 400,000 buildings that were constructed before 1919 [1]. It is intuitive that the repair and maintenance of these aging structures is becoming increasingly onerous due to degradation processes and the sheer age of the materials employed. Compounding this, it is well recognized that climate change is placing significant performance strain upon the existing built environment, ostensibly due to increased intensity and frequency of rainfall events in the UK [2] [3]. Within the context of a northern maritime climate, these buildings are wetter for longer and are often situated in environments with low potential evaporation [4]. Increased and accelerated deterioration of porous building materials subjected to saturated conditions is correlated with higher incidence of high and low order magnitude spalling associated with frost, increased biological activity, and salt related damage [5–8].

Aging fabric, twinned with increasingly aggressive environmental conditions, necessitates greater levels of contextualised building survey for effective targeted remedial intervention. Protocols and processes currently employed support conservation activities, ideally creating an objective datum for intervention. Nevertheless, these can be costly to undertake and place significant economic strain upon individuals and organisations entrusted with satisfactory building upkeep. These protocols are principally traditional in nature, adopting visual/manual evaluation of masonry elements, down to individual units. Additionally, inability to effectively record rubble masonry creates communication problems for those developing repair strategies, specifying remedial works or undertaking fabric intervention.

Attempts to record via hand drawing is cost prohibitive and is therefore only traditionally undertaken for buildings of the greatest significance or in the case of specialist studies focusing upon archaeological analysis or for academic purposes (see [9]). Furthermore, hand drawing is prone to inaccuracy due to its inherent complexity, resulting from a lack of uniformity, roundness and regularity of masonry units. Given this, a default of generic hatching (labelling) of the material is

---

* Corresponding author.
E-mail address: f.n.bosche@hw.ac.uk (F. Bosché).

https://doi.org/10.1016/j.autcon.2018.08.018
Received 31 October 2017; Received in revised form 18 May 2018; Accepted 29 August 2018
0926-5805/

applied to approximate areas to be highlighted. This is clearly insensitive in capturing and reflecting the reality of the as-built materials confronting the evaluator, hindering attempts to specifically identify areas requiring further assessment. In these situations, recording is therefore practically reduced to narrative description of the masonry wall area (in m^2) and cannot effectively reflect the complexity of the build. Importantly, such recording does not offer the ability to readily locate individual stones in what could be described as a ‘sea of stones’, causing communication problems for current and future information retrieval.

Attempts to enhance reporting uniformity have led to the utilisation of system-based approaches or protocols to survey [10] and whilst helpful, they cannot discount the inherent variation in surveyors' experience [11].

The use of state-of-the-art remote sensing technologies offers the promise of enhanced survey accuracy with the logical benefits that flow from primary characteristics such as cost, safety and objectivity. Reflecting this, various researchers have cumulatively progressed the body of knowledge on the value of these new technologies to support building surveying and maintenance activities.

In 1995, Ogleby [12] undertook a comprehensive review of techniques and technologies that existed for the generation of information adopted for the historic interpretation of monuments and sites of cultural significance. In that paper, the author focused on photogrammetric applications and the subsequent generation of CAD models. Further geospatial data acquisition technologies, and more specifically Terrestrial Laser Scanner (TLS) and photogrammetry, have revolutionized the recording and documentation aspects of historic buildings. Within the context of historic buildings surveying, Wilson et al. [13] illustrated the benefits of TLS contextualised upon complex UNESCO World Heritage sites, adopting a case study approach. Similar advances have been made using photogrammetry, taking advantage of rapid progress in photographic technology and computer vision. High-resolution cameras are now widely available at a relatively low cost, and the development of robust automated feature detection and matching in digital images, (e.g. SIFT [14] or SURF [15] features), as well as dense matching approaches [16] have considerably improved the image processing stage, enabling entirely automated processing pipelines. More recently, strategic use of Unmanned Aerial Vehicles (UAVs) for reality capture has been providing a new platform for photogrammetry to partially solve access issues. The value of UAVs to surveying has already been demonstrated in various contexts such as for ecological [17] or structural surveys [18]. These works illustrate how to obviate the use of scaffold and are therefore clearly beneficial in reducing acquisition time and cost. In the context of historic monuments, UAV-based photogrammetry has been shown to provide alternative solutions to TLS. For example, Puschel et al. [19] proposed the use of terrestrial and UAV pictures to capture and create an accurate 3D model of Castle Landenberg. Koutsoudis et al. [20] similarly proposed a photogrammetric system combining UAV and terrestrial pictures, and compared the resulting reconstruction with TLS, obtaining promising results.

These technologies have proven to be effective, delivering accurate 3D and colour measurements. However, the outcome obtained by the mentioned devices are in raw data form (point clouds) and require further processing to produce understandable semantically-rich information that can be interpreted by experts.

With respect to the analysis of geospatial data, initial identification of primary building volumes or entities can be considered as a 1st order structure tier, with 2nd order tiers including subdivisions into principle building components such as walls, roofs, etc. The segmentation of the individual masonry units can be considered as 3rd order structure tier. As noted earlier, such segmentation is rarely conducted, let alone systematically successfully achieved, due to the sheer number of stones, the lack of uniformity in the materials, and the subjectivity of the individual surveyors observing the structures. Yet, whilst difficult to achieve, this is an essential component of other tangible processes (i.e. effective costing of the works and the development of repair strategies).

Within this context, objective and cost-effective data processing methods are required to facilitate reporting and analysis. Automatic segmentation and further processing of data from modern reality capture technologies (i.e. TLS and photogrammetry) would facilitate surveying operations undertaken by surveying experts, enabling them to focus on value-adding activities such as conducting building pathology from identified defects, and developing in-depth repair strategies. Various research teams have been specially working on advancing this field. Most prominently, a semi-automatic delineation and masonry classification was developed by Oses and Dornaika [21] who used Artificial Intelligence techniques (k-NN classifiers) to identify stone blocks in 2D images. Additionally, Cappellini et al. [22] proposed a semi-automatic approach to semantically label 2.5D data (colour and depth information) of brick and stone walls obtained using photogrammetry.

Whilst data segmentation and subsequent calculations, in both visual and computer-based surveys, are relatively easy to achieve in brickwork, squared coursed rubble and ashlar, these calculations are inherently more complex in the case of random rubble masonry due to variability in stone and mortar dimensions. The objective of this paper is to present a novel approach to deal with the segmentation of masonry walls made of irregular rubble or ‘random’ rubble. The method, detailed in the next sections, is based on the analysis of 2.5D wall data (acquired by means of TLS) in the spatial frequency domain, by means of the 2D Continuous Wavelet Transform (CWT). This mathematical tool, as shown in [23], allows a detailed analysis at local level and is not sensitive to more global levels of flatness, waviness, curvature and plumbness of walls, which are commonly encountered in historic buildings.

The rest of the paper is structured as follows: Section 2 contains an introduction to the CWT. Section 3 describes the method designed for stone/mortar segmentation. Section 4 presents how such segmentation can effectively further analysis of value to building surveying and maintenance, with the example of mortar regression from the masonry surfaces. Section 5 introduces the experiments carried out to test the developed technique and reports the obtained results. Section 6 concludes the works and offers directions for future works.

2. 2D continuous wavelet transform for stone walls segmentation

The Wavelet Transform is a signal analysis method that is based on the convolution of the input signal with a wavelet function at different locations along the signal and at multiple scales. This enables the detection of the signal pattern of the wavelet function at potentially any scale and at any location [24].

The Continuous Wavelet Transform (CWT) is one of the several variants of the Wavelet Transform that is commonly considered for pattern or frequency detection in a signal. This can be applied to solve the problem of surface waviness characterizations [24]. It is important to highlight that CWT is not only applicable to 1D signals, but also to 2D signals, as presented in [25].

Applying the CWT, like any other WT, requires the selection of the mother wavelet. One common CWT wavelet is the Mexican Hat wavelet, as shown in Fig. 1. This 2D wavelet is composed of one main undulation with centre frequency f_c that is the same for both dimensions. The centre frequency of the Mexican Hat wavelet is $f_c = 0.252$. By convolving an input 2D signal with the Mexican Hat wavelet at a given scale a, undulations of characteristic frequency f can be detected, with f calculated as:

$$f = \frac{f_c}{\delta_p a} \tag{1}$$

where δ_p is the point sampling period in the input signal along the given dimension.