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Development of a novel simplification mask for multi-shot optical scanners

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ABSTRACT

Most optical scanners work based on a fix resolution and, thus, produce a huge number of points, many of which are usually redundant. Therefore, an intensive post-processing step is required to simplify the resulting point cloud. In this paper, a novel technique is proposed that does not require the post-measurement calculations; instead, it reduces the scanned points at the data-acquisition phase. For this, the surface curvatures of object points are determined using the photometric stereo. Then, the curvature values are classified based on an adaptive sampling interval which is defined through an innovative calibration process. Once the curvature ranges are identified as such, a simplification mask is created. The mask is a binary image that is used to show points in the image space the optical scanner requires to decide if the 3D coordinates of an object point need to be computed. Having evaluated the proposed method using a fringe scanner, we observed that, although the data acquisition time is slightly increased, the number of redundant points is notably reduced. Therefore, not only the production of unnecessary data is prevented by 71–90% (depending on the surface complexity), but also carrying out the intensive post-processing simplification step is totally avoided.

1. Introduction

Three-dimensional measurement is one of the primary interests of various applications such as industrial quality control (Almamou et al., 2015), documentation of cultural artefacts (Castellazzi et al., 2015) and medical image processing (Schwenzer-Zimmerer et al., 2008) . Contrary to the contact-based mechanical methods, image-based multi-shot techniques (e.g. (Abzal et al., 2011; Salvi et al., 2004)) have gained substantial attention. As an example, the digital fringe projection (DFP) method can capture a dense and very accurate point cloud from an object (Gorthi and Rastogi, 2010). Unfortunately, modelling or even visualisation of such points is usually a very time-consuming and costly process (Remondino, 2001). Therefore, the development of an efficient and accurate simplification of the point cloud is required.

There exist many simplification techniques, which can also be applied to the high-resolution data obtained from an optical scanner. The methods are numerous and, thus, can be categorised in different ways. For instance, (Abo-Surrah, 2014) considers the computation space to classify them into discrete fourier (Guo et al., 2002) and real spaces (Nothegger and Dorninger, 2009). In (Pauly et al., 2002), the authors group the simplification algorithms into three main types that include clustering, iterative, and particle simulation methods (Turk, 1992). As an example of such classification, (Zhang et al., 2004) developed a hierarchical clustering algorithm to simplify point cloud data by movable mesh generation. Similarly, (Orts-Escolano et al., 2013) uses growing neural gas as an iterative method for point cloud 3D simplification.

In (Dyn et al., 2008) the problem is viewed from the data structure perspective where, contrary to the point-based algorithms, a mesh-based approach is said to be more complicated. Examples here are (Turk, 1992) and (Zhang et al., 2004). (Ming et al., 2010) uses a mesh generation algorithm to simplify a point cloud while (Chouychai, 2015) uses the point-based method to find significant points by an interpolation technique. In a different attempt, the problem is described in two different ways. One is to specify the number of points in the final reduced data, and the other is to identify a threshold on the geometric deviation between the original and the simplified data sets. For example, (Pauly et al., 2002) uses the geometric deviation to evaluate the efficiency of the data-acquisition algorithm. (Song and Feng, 2009) presents a progressive simplification algorithm that repeated until the number of points reaches a specific number.

Looking at the literature, one can realise that all existing simplification methods work on the full resolution point cloud, which is typically very intense. Therefore, they have to go through high computational complexities such as searching for neighbour points in three-dimensional space (Du and Zhuo, 2009; Pauly et al., 2002), curve fitting (Liao et al., 2014) and extraction of the surface normal (Li et al., 2014). As a result, the point cloud generation encounters intensive

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computations, with extensive data most of which is redundant and could have been avoided in the first place. The issue is still an open problem.

In this paper, a novel simplification mask is proposed which works with a multi-shot scanner to prevent it from capturing unnecessary points, right from the beginning. In this respect, the scanner is provided with an image that defines the significant points need to be scanned to preserve the object details. This way, in addition to being light and accurate, the resulting point cloud does not require an intense simplification process. Moreover, as will be mentioned, all the calculations are carried out in 2D; thus producing the model of a point cloud obtained with a scanner accompanied with the simplification mask is much faster than that of an optical scanner alone.

In the following sections, the proposed method will be explained. Next, evaluations carried out are reported in section 3, while section 4 concludes the paper and offers possible enhancements for future studies.

2. The proposed method

As mentioned, the primary goal of the proposed method is to create a simplification mask. The mask is a binary image used by the scanner to see if the 3D coordinates of an object point need to be computed or not. The general stages of the proposed method are shown in Fig. 1. First, the surface normals of the object are estimated using a Photometric Stereo (PS) technique (Woodham, 1980) (Fig. 1b). From these, the curvature values are calculated (Fig. 1c). The curvatures are, then, grouped into several ranges based on an adaptive sampling interval defined through a new and advanced calibration process (Fig. 1d). The adaptive interval is determined in a way that each part of the object which has a different curvature, be scanned with a different resolution. The curvature ranges are used to segment the curvature image (Fig. 1e), and the simplification mask is finally created (Fig. 1f).

In the following sections, these steps are described in detail.

2.1. Surface normal and curvature computation

In order for the scanner to acquire only the significant points, the geometric characteristics of the object have to be known. In this respect, the curvatures of the object surfaces are used. To determine the curvature values, we use the Photometric Stereo technique. The object is illuminated from different directions (Woodham, 1980), and series of images are taken. Provided that the object surface is Lambertian and the light source beams are parallel, the value of an image pixel depends on the albedo as well as the cosine of the incident angle which is obtained from the dot product of the light source and surface normal vectors. The relation between any point and its irradiance is described as (Nayar et al., 1991):

$$I_s = K_D \cos(\varphi_i) = K_D(n.\ L_s), \tag{1}$$

where, $K_D$is albedo, n is normal vector, $L$is the incident light direction, φ_i is the incident angle and $s$is the index of light sources.

The PS technique faces three types of errors (Woodham, 1994), the main ones of which concern the highlight or shadow (Barsky and Petrou, 2003; Hernández et al. (2008); Sun et al., 2007), near light sources (Ahmad et al., 2013; Papadhimitri and Favaro, 2014) and inter-reflection regions (Herbort et al., 2013; Liao et al., 2011; Nayar et al., 1991). To exclude the highlight and shadow pixels from the PS computations, a simple technique developed by (Sun et al., 2007) which has a low computation cost is used in this paper.

Furthermore, the assumption of having parallel light sources is violated when the light sources are close to the object. Thus, the calculated normals contain a low-frequency error which can be seen as a soft convex curvature. To solve this problem, for each pixel the light source direction elements need to be calculated separately. Therefore, the 3D positions of any light source and its distance from each object point have to be determined. For this, the method described in (Papadhimitri and Favaro, 2014) which iteratively minimises an energy function is used. The reason for choosing this approach is that it can handle unknown variant illuminations without performing a calibration of any kind. Also, it requires no assumptions regarding the geometry of the object nor its reflectance or the property of the light used.

The inter-reflection caused by indirect illumination of concave surfaces is the third major source of error in the PS technique. This error affects the computed normal and deforms the appearance of the scene significantly. Several methods have been proposed to correct this error (Herbort et al., 2013; Liao et al., 2011; Nayar et al., 1991; Sohaib et al., 2015). The method offered by (Herbort et al.,2013) is used in this research as is compatible with the light sources close to the object.

Once the normal vectors are available, the curvatures of the surface parts can be computed. In this regard, the method proposed by (Woodham, 1994) is used. According to (Woodham, 1994), the main curvature components, $k_1$and $k_2$are the eigenvalues of C as shown in Eqs. (2) and (3):

$$C = (1 + p^2 + q^2)^{-\frac{3}{2}} \begin{bmatrix} q^2 + 1 & -pq \\ -pq & p^2 + 1 \end{bmatrix} H, \tag{2}$$

$$H = \begin{bmatrix} p_x & p_y \\ q_x & q_y \end{bmatrix}, (p,\ q,\ 1) = (\frac{nx}{nz}, \frac{ny}{nz}, 1), \tag{3}$$

where $(p,\ q,\ 1)$are the surface gradient values while H is the Hessian matrix. The overall curvature $K = k_1 k_2$can also be calculated directly from Eq. (4):

$$K = \frac{1}{(1 + p^2 + q^2)^2} \det(H), \tag{4}$$

As a sample, Fig. 2c shows$|K|$of an object with a simple shape.

2.2. Calibration and sampling interval identification

As mentioned before, an optical scanner uses a fix sampling interval to scan the whole object. This usually leads to a dense cloud that includes many redundant points. To solve this problem, various sampling intervals are needed to make sure parts having a different level of complexities are scanned with different resolutions. In this section, it is shown how proper sampling intervals are determined through an advanced calibration. The calibration is carried out only once and results in a 2D simplification mask.

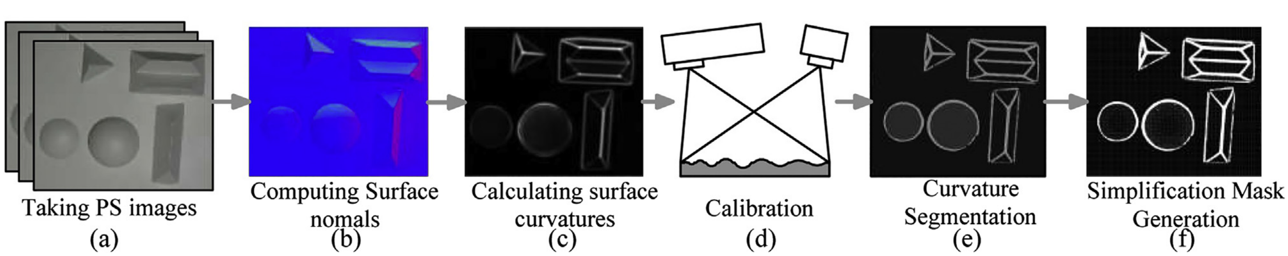

Fig. 1. Pipeline of the proposed method.