Graphical Models 94 (2017) 1–13

Contents lists available at ScienceDirect

Graphical Models

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

An algorithm for the rapid generation of bas-reliefs based on point clouds

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ARTICLE INFO

Article history:
Received 16 March 2017
Revised 1 September 2017
Accepted 8 September 2017
Available online 9 September 2017

Keywords
Bas-relief
Detail preservation
Normal vector
Point clouds

ABSTRACT

This paper proposes an algorithm for the rapid generation of bas-reliefs based on point clouds, which involves two steps: generation of a coarse model and establishment of fine mesh surfaces of the model. In the first step, a modified Z-Buffer algorithm is adopted to designate the visibility of every point before control points in a gridded distribution are arranged on the base plane of a relief. Afterwards, under the constraints of depth and normal information, the optimal compression ratio of the control points is obtained through use of a linear solution. For the compression ratio, bilinear interpolation is performed to generate an original model of the relief. In the establishment of the fine mesh surfaces, an index for measuring surface changes is proposed to adjust the height of the relief once again so as to highlight its detailed features. The aforementioned algorithm is verified by experimental work.

1. Introduction

With planes or surfaces as carriers, bas-reliefs are a kind of sculpture produced by compressing solid models into limited spaces and are extensively applied in product packaging, appearance adornment, the production of commemorative coins, etc. [1]. Traditional generation of reliefs that is highly dependent on manual work is characterised by low levels of automation in the design and manufacturing, which makes it hard to meet individual, diverse demands. In recent years, with the continuous development of 3D measuring and digital geometry processing technologies, 3D model-based algorithms for rapid generation of digital bas-reliefs have been extensively studied in the field of computer graphics.

On the whole, the technology for generating digital bas-reliefs can be classified into three classes. For the first type, an experienced artist is required to make a relief model using a specific material. Then, the model is detected using a 3D scanner to obtain key information about it. Visibly, this method involves a complicated abstract process including a large amount of work as well as a very accomplished designer. As for the second, according to the mapping relationship of grey values, information can be extracted from 2D images to generate a bas-relief model, most commonly by adopting the shape from a shading algorithm, a method for the reconstruction of 3D images [2–4]. By processing images, this type of method offers a high computing speed on account of data alignment rules, but details of the bas-relief are not expressed satisfactorily apart from those possible at low levels of automation with plenty of human-computer interaction [5]. The third type produces a bas-relief through height compression in a 3D data model established by scanning a material object along a certain viewing direction, which is so intuitive and highly automated that it can be performed by any non-professional person. In accordance with the operands in height compression, this method can also be sub-classified into two types: one based on the depth domain, the other based on the gradient domain of a model. Thereinto, with the 3D coordinates of the model as the direct operand, the depth-domain based method is simple, easy to implement, and rapid, regardless of its deficiencies in describing details at large compression scales. Through processing the differential coordinates of the model and solving Poisson's equation, the gradient-domain based method can produce a relief that maintains the characteristic of the differential domain. With this method, any reliefs generated are expected to retain the original details, while the efficiency is lower than that of the former method due to the need to solve a large, sparse, partial differential equation.

At present, most algorithms used for generating bas-reliefs use mesh surfaces as their input. Nevertheless, with the development of structural light measurement technologies, especially the wide application of Kinect depth transducers, more original data for 3D models are obtained in the form of point clouds [6,7]. It is a challenge work to generate a mesh surface by using scattered point clouds. Interpolation, and implicit surface, methods are currently used: as for these algorithms, users generally need to establish

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http://dx.doi.org/10.1016/j.gmod.2017.09.002
1524-0703/© 2017 Published by Elsevier Inc.

many parameters, and inappropriate parameter settings may cause a loss of model details. Based on point cloud data, this paper proposes an algorithm for rapid generation of bas-reliefs, which adopts a coarse-to-fine generation strategy. First, control points, in a gridded distribution, are laid out on a base plane of a relief and the compression ratio of the control points is solved under the constraints of depth and normal information. Then, according to the obtained compression ratio, bilinear interpolation is conducted to obtain the relief height of each point in the point cloud. Afterwards, based on the revised smooth shrinkage index (RSSI), an index for measuring surface change based on the shrinkage when performing mean-value smoothing, the height of the relief is readjusted to accentuate its detailed features. In the end, through multilevel B-spline fitting, gridded point cloud data are obtained to establish the mesh surface of the relief. This study proposes the following as novel: (1) it proposes an algorithm for generating reliefs with point clouds and mesh surfaces as the input and output, respectively. Compared with existing algorithms, this algorithm is characterised by high speed and efficiency in that it avoids the need to re-establish surfaces from point clouds and possible problems such as detailed information loss from original models in its surface reconstruction. (2) A linear algorithm for solving the height of control points of a relief is presented, which takes both depth and gradient information into account. By using the distribution characteristic of the control points, a linear equation for the height of control points is achieved from the constraint relationship relating to the maintenance of the normal vector information of the control points, and it allows the height of control points to have a closed-form solution. (3) The existing measure index for surface changes, SSI, is modified and used to readjust the height of a relief so as to optimise the performance of detail-carving stages of the process. Also, the refinement of its ability to depict details can be adjusted by users.

The remaining parts of this paper are organised as follows: Section 2 presents the relevant literature, followed by an introduction of the proposed algorithm for the generation of reliefs and the details in its application in Section 3, Section 4 discusses the verification of the algorithm's feasibility through experiments together with a comparison between it and other key algorithms, conclusions are drawn, and further research directions are indicated, in Section 5.

2. Related work

As the digital technology of material objects develops, more 3D model-based methods for designing bas-reliefs are being investigated. The core problem is to compress a 3D model without changing its initial saturation, local features, and spaciousness. According to different operands, algorithms for generating bas-reliefs can be classified into two classes: one based on the depth domain, the other based on the gradient domain of a model [8].

2.1. The depth-domain-based algorithm

By transforming the height field of a model through linear or non-linear functions, the depth-domain based algorithm for generating bas-reliefs is capable of mapping 3D models directly into bas-relief surfaces. The algorithm was first studied by Cignoni et al. [9] in 1998. In their research, perspective projection and the Z-Buffer algorithm for graphical display are used to obtain depth values so as to perform linear compression. Despite simplicity, and high efficiency, this algorithm readily causes the loss of detailed features, so that it fails to acquire a favourable relief than more complicated models. Other researchers have proposed new depth compression approaches on the basis of the geometrical characteristic of a model. For example, an adaptive histogram equalisation (AHE) method for image processing, which is applied in 3D models can determine the depth compression coefficient by equalising the gradient weighted histogram for the depth value of a model [10]. This method performs well with regard to the preservation of features and definition of the details of obtained reliefs, but lacks efficiency as a result of the high time complexity of AHE and the onerous establishment of the six parameters involved. Furthermore, AHE needs to be recalculated when any of the parameters changes. In addition, according to the frequency distribution of the model, a mesh surface is decomposed into smaller surfaces to allow depth compression [11]. Although the reliefs achieved with this method maintain the detailed features more favourably, the method is still inefficient when processing large-scale mesh data. Besides, a bilateral filtering algorithm is used to extract detailed features from an overall model and especially considers these features in its height compression [12]. As it does not need to solve complicated differential equations, this algorithm has a high operating rate. However, due to its neglecting gradient information in height compression, the reliefs obtained are deficient in saturation apart from the inconspicuous multilevel relationships where the surface changes slowly. On the whole, as no conversion of depth field and gradient field is involved, the depth-domain based method can work at a high operating rate. Whereas, owing to the operation only being conducted in the depth field, the gradient information of the original model is easily lost, leading to low saturation of the resulting bas-reliefs.

2.2. The gradient-domain-based algorithm

By using the gradient-domain algorithm for generating bas-reliefs, depth information of a model is transformed into the gradient domain where the height field is compressed before the relief model is transformed to depth domain again. Thereinto, Song et al. [13] first measured, projected, and then expressed the saliency of visual features of a mesh model under given observation conditions in the form of differential coordinates in accordance with the concept of mesh saliency [14]. Afterwards, an unsharp masking technology based on the Gaussian kernel was used to strengthen the detailed features before solving Poisson's equation to rebuild the depth domain so as to obtain a relief surface. The saliency describes the variation in the curvature of a model, and therefore, the above algorithm can retain some detailed characteristics of the model. However, to simplify the operation, the first-order partial derivative of a source model was assumed to be zero, which has been proved to be unreasonable. As a result, evident deformation is found in some parts of the resulting reliefs. In addition, Weyrich et al. [15] applied the compression technology for the gradient domain of images with a high dynamic range [16] in the design of reliefs, that is, the reliefs were designed through the non-linear compression of gradient values of 3D models. By using this method, the areas with large or small gradient values are correspondingly compressed to a large or small extent, separately, which allows the bas-reliefs to maintain their detailed information. Besides, diffusion filtering for boundary maintenance was used to preserve the discontinuous characteristics of the gradient domain, in combination with the multi-scale method for the differentiation of the importance of discrepant frequency characteristics, which made the design of bas-reliefs less restrictive. Consequently, the generated bas-reliefs were endowed with distinct shapes, abundant detail, etc. However, the overall efficiency of the algorithm is unsatisfactory as its parameters are less intuitive and model-dependent, which calls for numerous user-interactive set-up operations. Kerber et al. [17] used the idea in the previous