PATTERN-BASED 3D MODEL COMPRESSION

CAI Kangying  JIANG Wenfei  LUO Tao  TIAN Jiang

technicolor R&D

ABSTRACT

This paper presents an efficient method to 3D model compression based on repetition detection. The proposed Pattern-Based 3D Mesh Codec (PB3DMC) can achieve good rate-distortion performance on 3D models comprising multiple components. The repetition among constituent components is first exploited to generate a compact representation. An optimal bit allocation scheme is then proposed in order to compress the resultant “pattern-instances” representation. Experimental results show that PB3DMC yields a significant gain compared to the algorithms in MPEG’s Scalable Complexity 3D Mesh Coding (SC3DMC) toolset, particularly for those models containing repetitive components. Furthermore, a benchmark for PB3DMC is built using 444 models. And PB3DMC is going to be published as an amendment of MPEG-4 standard.

Index Terms— 3D model, Coding, repetitive component, bit allocation, MPEG

1. INTRODUCTION

The easy access to 3D modeling tools and rapid growth of online modeling communities make the quantity and complexity of 3D models increased continuously. And the widely used 3D modeling tools usually generate 3D models containing a significant number of components, especially when creating complex objects. Thus, efficient compression solutions are required to overcome the challenges in storage and transmission. For multi-component 3D models, it is straightforward to decompose them and compress each individual component using previous methods based on geometry primitives, such as vertex spatial position [1, 2], adjacency [3, 4, 5], local geometric features [6, 7].

However, there usually exists redundancy among the structures of constituent components. To improve the efficiency of 3D model coding techniques, the structural regularity can be exploited. Recently, symmetry detection on 3D models has received much attention [8, 9, 10]. Therefore, the detected symmetries can produce a compact representation of 3D model, such as a tree-structure [11, 8] or a hierarchy [12]. Digne et al. [13] proposed to compress point cloud by exploiting the self-similarity of the underlying shape. For image representation, the approaches to factoring repetitive content have also been developed. In [14], Wang et al. proposed to create a condensed epitome and a transformation map such that all image blocks can be represented from transformed epitome patches. In our method, repetition is explored among the components of 3D model, which is a kind of geometric invariance under translation, rotation transformation or their combinations. The so-called “pattern-instances” representation derived from repetition detection is compact and beneficial to improve the performance of the proposed PB3DMC.

In order to encode the “pattern-instances” representation, an optimal bit allocation scheme is proposed in this paper. Different from the existing 3D model compression algorithms based on repetition detection [13, 15], PB3DMC determines the optimal quantization parameters automatically for various data in the repetition-aware representation. For instance, the quantization parameter of each rotation transformation is adaptively decided by the parameter of global quality and the scale of the corresponding component. To the best of our knowledge, it is the first time to concentrate on bit-rate allocation in the compression techniques based on repetition detection. And compared to the “instancing” techniques widely used by real-time engines for gaming, one important advantage of the proposed method is that the encoder requires no prior knowledge of the input 3D models.

In this paper, a benchmark is built for PB3DMC including 444 models provided by MyMultiMediaWorld.com [16]. As demonstrated in experimental results, PB3DMC makes a significant gain compared to the algorithms in MPEG’s SC3DMC [17] toolset. And the bitstream format and decoder of PB3DMC are going to be published as one of the amendments in MPEG-4 Part 16 [18]. The 3D graphics group of MPEG (MPEG-3DG) has standardized several compression techniques for 3D models, which are introduced in MPEG-4 Part 2, Visual (3DMC) and MPEG-4 Part 16, Animation Framework eXtension (3DMC-Extension and SC3DMC). SC3DMC is introduced in MPEG-4 Part 16 AMD 4 in year 2009, which consists of 5 different ways with different compression performances and complexities to enlarge the application domain of MPEG-4 3DG.
2. COMPRESSION ALGORITHM

The framework of PB3DMC encoder is as shown in Fig.1. The inputs are the 3D model to be encoded and one quantization parameter \( QP \) given by the user. Then the maximum reconstruction allowed, \( MaxErr \), could be derived from \( QP \) and the boundingbox of the input model. The encoder consists of three steps, repetition discovery, repetition compression and instance verification.

The first step is achieved by pair-wise component comparison, which can be accelerated by grouping components using their feature descriptors. \( MaxErr \) is used as the threshold during the comparison. Then the input 3D model is transformed into the new representation consisting of patterns, instances and unique parts. Here a pattern refers to the representative geometry of a discovered repetitive structure, which has been aligned with the coordinate system. An instance is represented by the transformation matrix \( M \), from its corresponding pattern to this instance part, and the related pattern’s ID. \( M \) is further decomposed into translation vector \( T(t_x, t_y, t_z) \) and rotation matrix \( R \), which is represented by the Euler angles \((\psi, \theta, \phi) \ (\theta \in [-\frac{\pi}{2}, \frac{\pi}{2}], \psi, \phi \in [-\pi, \pi])\). The unique parts are those not belonging to any repetitive structures.

In the second step, the patterns and unique parts can be encoded by any mature 3D model codec. \( T \) and \((\psi, \theta, \phi)\) are quantized and further compressed by an entropy codec. \( QP_P \), \( QP_T \) and \( QP_A \), the quantization parameters of pattern, \( T \) and \((\psi, \theta, \phi)\), are automatically determined by an optimal bit allocation scheme which could make the maximum reconstruction error meets the user requirement, i.e. \( MaxErr \). Especially, to avoid unnecessary bit-rate loss, different instances use different values of \( QP_A \), denoted as \( QP_A^i \), which are related with the correspondent component scales. More details will be given later. For unique parts, \( QP \) is used as its quantization parameter. Furthermore, to guarantee the required reconstruction error, an instance verification step is followed. This step reconstructs every instance component to verify whether or not its maximum reconstruction error is less than \( MaxErr \). Those fail to pass the test are compressed together with the unique parts discovered in the first step.

The compressed bitstream consists of \( QP \), the bounding-box of the 3D model, the bounding-box of all translation vectors, the encoded unique parts, encoded patterns along with pattern IDS and encoded instance transformation matrices along with instance IDs. Another advantage of the bit allocation scheme used by PB3DMC is that \( QP_P \), \( QP_T \) and \( QP_A^i \) can be automatically decided by the decoder. Except the bounding-box of translation vectors, there is almost no bit-rate loss for recording different quantization parameters. The decoder decodes all the data and reconstructs instance components using the reconstructed patterns and transformation matrices.

2.1. Bit Allocation Optimization

The optimal values of \( QP_P \), \( QP_T \) and \( QP_A^i \) are automatically determined from \( QP \) by figuring out their contribution to the final reconstruction error. During the following discussion, the vertex-vertex error is used as the reconstruction error. Here the goal is to guarantee that the maximum reconstruction error is less than \( MaxErr \).

Any vertex \( v \) on any instance component can be represented by

\[
\mathbf{v} = \mathbf{R} \mathbf{p} + \mathbf{T},
\]

(1)

where \( \mathbf{p} \) is the correspondent vertex on pattern \( \mathbf{R} \) and \( \mathbf{T} \) are the rotation matrix and translation vector from \( \mathbf{p} \) to \( \mathbf{v} \).

Let \( \mathbf{v}_d \) denote the reconstructed vertex. Then the reconstruction error of \( \mathbf{v} \) can be calculated as:

\[
\|\mathbf{v} - \mathbf{v}_d\| = \|\mathbf{R} \mathbf{p} + \mathbf{T} - \mathbf{R} \mathbf{p}_d - \mathbf{T}_d\| \\
\leq \|\mathbf{R} \mathbf{p} - \mathbf{R} \mathbf{p}_d\| + \|\mathbf{R} \mathbf{p}_d - \mathbf{p}_d\| + \|\mathbf{T} - \mathbf{T}_d\| \\
\leq \|\mathbf{R} - \mathbf{R}_d\|\mathbf{p} + \|\mathbf{D} \mathbf{p}\| + \|\mathbf{D} \mathbf{T}\|,
\]

(2)

where \( \mathbf{p}_d, \mathbf{R}_d \) and \( \mathbf{T}_d \) are the reconstructed \( \mathbf{p}, \mathbf{R} \) and \( \mathbf{T} \). \( \mathbf{D} \mathbf{p} = \mathbf{p} - \mathbf{p}_d \) and \( \mathbf{D} \mathbf{T} = \mathbf{T} - \mathbf{T}_d \) are the reconstruction error of \( \mathbf{p} \) and \( \mathbf{T} \).

We have

\[
\|\mathbf{R} - \mathbf{R}_d\|\mathbf{p} \leq c_\mathbf{p} \Delta \theta_{\max} \|\mathbf{p}_{\max}\|,
\]

(3)

where \( \Delta \theta_{\max} \) is the upper bound of quantization error of the three Euler angles and \( c_\mathbf{p} \) is an constant which can be estimated from experiments. In our experiments, \( c_\mathbf{p} = \sqrt{2} \).

From Eq. 2 and Eq. 3, the optimization goal here can be written as

\[
c_\mathbf{p} \Delta \theta_{\max} \|\mathbf{p}\|_{\max} + \|\mathbf{D} \mathbf{p}\|_{\max} + \|\mathbf{D} \mathbf{T}\|_{\max} = MaxErr,
\]

(4)

where \( \|\mathbf{D} \mathbf{p}\|_{\max} \) and \( \|\mathbf{D} \mathbf{T}\|_{\max} \) are the upper bounds of the reconstruction error of pattern coordinates and translation vectors, and \( \|\mathbf{p}\|_{\max} \) is the scale of the pattern.

Intuitively, let the three items at the left side of Eq. 4 to be equal, i.e.

\[
c_\mathbf{p} \Delta \theta_{\max} \|\mathbf{p}\|_{\max} = \|\mathbf{D} \mathbf{p}\|_{\max} = \|\mathbf{D} \mathbf{T}\|_{\max} = \frac{MaxErr}{3}.
\]

(5)
By using Eq. 5, the various quantization parameters can be decided from QP as follows.

\[ QP_p = [3e_{QP}QP] \]  

(6)

where \( e_{QP}(0,0,1,0) \) is a constant used to control the influence of the over-conservative estimation of the reconstruction to the final rate-distortion (RD) performance. In our experiments, \( e_{QP} = 0.4 \).

The patterns will be translated to the origin before compression. All patterns will be compressed together. Then

\[ \|\Delta p\|_{\text{max}} = 2^{-QP_p-1}S_{P_{\text{max}}} \]  

(7)

and

\[ \|\Delta T\|_{\text{max}} = 2^{-QP_T-1}S_T \]  

(8)

where \( S_{P_{\text{max}}} \) is the scale of the pattern with the biggest bounding-box, and \( S_T \) is the bounding-box of all translation vectors. Using Eq. 5, \( QP_T \) can be calculated by

\[ QP_T = [QP_p + \log_2 \frac{S_T}{S_{P_{\text{max}}}}] \]  

(9)

For calculating \( QP_A \), an important fact which can also be observed from Eq. 5 is that the distortion caused by quantizing Euler angles varies with the scale of the correspondent pattern. Thus, to achieve the same reconstruction error, relative small instance components need less accurate quantization of the rotation transformation than the big ones. To avoid unnecessary bit-rate loss, rather than calculating a single \( QP_A \) for all instances, \( QP_A \) is calculated for each instance using the correspondent pattern scale as follows.

As

\[ \Delta \theta_{\text{max}} = 2\pi 2^{-QP_A-1}, \]  

(10)

using Eq. 5 and Eq. 7, \( QP_A \) is calculated by

\[ QP_A = [QP_p + \log_2 \frac{2\pi e_{QP}S_p}{S_{P_{\text{max}}}}] \]  

(11)

where \( S_p \) is the scale of the pattern corresponding to the \( i_{th} \) instance.

Furthermore, to make sure that the same values can be calculated by the decoder, \( QP_T \) and \( QP_A \) are given by

\[ QP_T = [QP_p + \log_2 \frac{S_T}{S_{P_{\text{max}}}}] \]  

(12)

\[ QP_A = [QP_p + \log_2 \frac{2\pi e_{QP}S_p}{S_{P_{\text{max}}}}] \]  

(13)

where \( S_{P_{\text{max}}} \) and \( S_p \) are the scale of the reconstructed patterns. Then the decoder can automatically decide the quantization parameters after recovering all patterns.

3. EXPERIMENTAL RESULTS

Various experiments are performed to compare the RD performance of PB3DMC and SC3DMC. During all the experiments, the configuration of SC3DMC which generates the best performance is used. PB3DMC also uses SC3DMC with the same configuration to compress patterns and unique components. Multi-component 3D models with a wide range of complexity and topology types have been used in our experiments. RMS calculated by Metro [19] is used as the measure of the reconstruction error. The distortion is reported with the respect to the diagonal of the bounding box of the original 3D model.

![Fig. 2. Experiment to test the bit allocation scheme.](image-url)
Fig. 3. The RD performance curves of 5 models from the Princeton Shape Benchmark. In the sense of the distortion is less than 0.001, m453, m414, m599, m973 and m1056 have 70%, 95%, 82%, 73% and 75% vertices belonging to repetitive structures.

Decoding time comparison

Fig. 4. Decoding efficiency comparison.

Finally, a benchmark is built for PB3DMC using 444 multi-component 3D models from MyMultiMediaWorld.com. The RD gain of PB3DMC over SC3DMC is as shown in Fig. 5. Except 7 models which PB3DMC performs a bit worse than SC3DMC (< −10%), PB3DMC achieves significant gain, more than 50% gain on more than 80% 3D models. Besides the efficient design of PB3DMC, this significant performance gain is also based on the fact that these 3D models are built for the common objects in the real world, such as plants and architectures, and contain a large number of components. Similar results are reported in [21].

4. CONCLUSIONS

In this paper, a Pattern-Based 3D Mesh Codec is presented to compress multi-component 3D models. The repetition among the components is exploited to reduce the redundancy, which benefit the performance of the proposed method. And an optimal bit allocation scheme is proposed to encode the compact representation derived from repetition detection. Compared with the previous standardized algorithms, a significant gain can be obtained using the proposed PB3DMC, which will be published as an amendment of MPEG-4 standard.
5. REFERENCES


