A 3-D Mesh Watermarking Scheme with Highpass Filter

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Abstract

In this paper, we investigate a blind watermarking algorithm based on a highpass filter for three-dimensional (3-D) meshes. For improving watermark detection in correlation-based watermarking, our scheme employs the highpass filter which emphasizes an impulse signal embedded as a signature into a host mesh. In the proposed method, we align the host mesh by the principal component analysis and convert from orthogonal coordinates to polar coordinates. After this preprocessing, we map the 3-D data onto a 2-D space via block segmentation and average operation, and rearrange for the 2-D data to an 1-D sequence. On the 1-D space, we apply a complex smear transform and a highpass filter. From the resulting signal, we derive the optimum complex-valued impulse signal in terms of the Euclidean norm. To generate a watermark with desirable properties, similar to a pseudo-noise signal, we perform a complex desmear transform, which is the inverse system to the complex smear transform, on the complex-valued impulse signal. After reordering into the 2-D signal and 3-D mapping from the 2-D space, the watermark is embedded into the host mesh and the resulting mesh is converted to orthogonal coordinates. At the decoder, we implement an inverse process with the highpass filter for stego meshes and detect a position of the maximum value as a signature. For a 3-D Bunny model, detection rates are shown to evaluate the performance of the proposed algorithm.

1. Introduction

There has been a significant growth in the field of digital watermarking [1]. One of image watermarking approaches is spread spectrum technique [2], where the watermark is a pseudo-noise (PN) signal generated from a secret key. To detect this signature in the watermarked image, a correlation between the PN signal and the watermarked image is calculated. According to the correlation value, a detector can obtain the embedded message by the correct key. In addition to image watermarking, three-dimensional (3-D) mesh watermarking was first introduced in [3], where 3-D meshes include Virtual Reality Modeling Language and computer-aided design.

In the recent years, several 3-D watermarking methods have been presented in [4]-[6] to improve the performance in terms of perceptual transparency, robustness and payload of the watermark.

In this paper, we propose a blind watermarking technique with highpass filtering for 3-D polygonal meshes. Similar to the PN signal in spread spectrum watermarking, we utilize a spread spectrum code as the watermark which is derived by a complex smear/desmear transform [7] for an impulse signal. In our watermarking method, a position of a nonzero sample in the impulse signal serves as an embedded signature. The complex smear/desmear transform for the impulse signal disperses the energy in the spatial domain and generates an orthogonal polyphase sequence with complex-valued samples for incorporating imperceptibility and robustness. For emphasizing this signature at the decoder side, we take advantage of highpass filtering, because typical meshes are composed of low frequency components. At watermark embedding, we employ the following watermark detection processes for a host mesh: a conversion to polar coordinates, 2-D mapping from 3-D data, converting into an 1-D sequence, the complex smear transform, and highpass filtering. By this procedure, we derive the optimum impulse signal, i.e., signature. For obtaining a watermarked mesh, an inverse process to watermark detection, except for highpass filtering, is implemented for this impulse signal and the resulting watermark is added to the host mesh. To detect the watermark, normalization via the principal component analysis (PCA) [8], conversion, mapping, reordering and complex smear transform are applied to the watermarked 3-D model and we utilize a highpass filter at the end of watermark detection. The position of the peak value in the obtained signal results in a detected message. Various comparisons with the watermarking scheme without highpass filtering are shown to demonstrate the validity of the proposed scheme.

2. Proposed Watermarking Scheme

In this section, we present a 3-D watermarking technique based on [6]. This method embeds watermark information into a 3-D mesh by adding a spread spectrum code generated from an impulse signal on an 1-D space. The watermark in
the stego mesh model is extracted by a correlation-based detec-
tor. In this paper, we introduce a highpass filter for watermark
detection with the aim of increasing robustness of the
watermark. Both the watermark embedding and extraction
processes are described in the following subsections.

2.1 Watermark embedding

Fig. 1 depicts a block diagram of watermark embedding for the
proposed watermarking method. After introducing centered
vertices, we utilize a PCA-based method (8), where the
vertices. In order to align the 3-D mesh in a normalized coor-
dinate system, we perform the normalization and conversion
to orthogonal coordinates. After a detection procedure
for a host watermark from an 1-D impulse signal with
complex valued samples. We then begin with a detection
procedure for a host watermark from an 1-D impulse signal with
complex valued samples. We then begin with a detection
procedure for a host watermark from an 1-D impulse signal
With (8), where the PCA is an abbreviation of the principal component analysis.
After introducing centered vertices

\[ \mathbf{v}_i' = \mathbf{v}_i - \mathbf{v} \quad \mathbf{v} = \frac{1}{V} \sum_{i=0}^{V-1} \mathbf{v}_i \]  

(1)

we calculate three eigenvectors \( \mathbf{c}_t \) \( (t = 0, 1, 2) \) with eigenval-
ues \( \lambda_t \) of a covariance matrix

\[ \mathbf{C} = \frac{1}{V} \sum_{i=0}^{V-1} \mathbf{v}_i' \mathbf{v}_i'^T \]  

(2)

where \( \lambda_0 \geq \lambda_1 \geq \lambda_2 \). If the \( t \)-th element \( \mathbf{c}_t(t) \) of the eigenvector \( \mathbf{c}_t \) is negative, we replace \( \mathbf{c}_t \) by \( -\mathbf{c}_t \), i.e., \( \mathbf{c}_t = -\mathbf{c}_t \). We then transform \( \mathbf{v}_i' \) into \( \mathbf{v}_i'' \) in the normalized coordinate system as

\[ \mathbf{v}_i'' = \begin{bmatrix} x_i'' \\ y_i'' \\ z_i'' \end{bmatrix} = \mathbf{a}^T \begin{bmatrix} \mathbf{c}_0^T \\ \mathbf{c}_1^T \\ \mathbf{c}_2^T \end{bmatrix} \]  

(3)

where \( \mathbf{a}^T \) denotes the transpose of the vector \( \mathbf{a} \). In addition to
this normalization, we convert from orthogonal coordinates

\[ \mathbf{v}_i'' \] to polar coordinates \( \mathbf{p}_i = \begin{bmatrix} r_i \\ \theta_i \\ \phi_i \end{bmatrix} \) as

\[ r_i = \sqrt{x_i''^2 + y_i''^2 + z_i''^2} \]

\[ \theta_i = \arctan \frac{y_i''}{x_i''} \]

\[ \phi_i = \arctan \frac{z_i''}{\sqrt{x_i''^2 + y_i''^2}} \]  

(4)

The polar coordinates \( \mathbf{p}_i \) are mapped to 2-D data \( \mathbf{R} = [r(m, n)] \) as

\[ r(m, n) = \frac{1}{|S_{m,n}|} \sum_{i \in S_{m,n}} r_i \]  

(5)

for \( m = 0, 1, \ldots, M - 1 \) and \( n = 0, 1, \ldots, N - 1 \)

where

\[ S_{m,n} = \left\{ i \mid \frac{\pi}{M} m \leq \theta_i < \frac{\pi}{M} (m + 1), \frac{2\pi}{N} n \leq \phi_i < \frac{2\pi}{N} (n + 1) \right\} \]  

(6)

and \( |S_{m,n}| \) denotes the cardinality of the set \( S_{m,n} \). After a
real-to-complex conversion from \( \mathbf{R} \) to \( \mathbf{Y} = [y(m', n)] = [r(2m', n) + jr(2m' + 1, n)] \) for \( m' = 0, 1, \ldots, \frac{M}{2} - 1 \), we reord
er the 2-D data \( \mathbf{Y} \) to an 1-D sequence \( \mathbf{l} = [l(i)] \) as

\[ l \left( \frac{M}{2} n + m' \right) = y(m', n) \]  

(7)

A complex smear transform for \( \mathbf{l} \) is expressed by

\[ \mathbf{s} = \frac{1}{7} \mathbf{W}_l^* \cdot \mathbf{C}_l \cdot \mathbf{W}_l \cdot \mathbf{l} \]  

(8)

\[ \mathbf{W}_l = \begin{bmatrix} e^{-j\frac{2\pi}{7}(0)/1} & e^{-j\frac{2\pi}{7}(1)/1} & e^{-j\frac{2\pi}{7}(2)/1} \\ e^{-j\frac{2\pi}{7}(0)/1} & e^{-j\frac{2\pi}{7}(1)/1} & e^{-j\frac{2\pi}{7}(2)/1} \\ \vdots & \vdots & \vdots \end{bmatrix} \]
work, we employ the following zero-phase filter
\[ \cdots e^{-j2\pi0(I-1)/I} \]
\[ \cdots e^{-j2\pi1(I-1)/I} \]
\[ \vdots \]
\[ \cdots e^{-j2\pi(I-1)(I-1)/I} \]
\[ D_I = \text{diag} \left( e^{-j(0)}, e^{-j(1)}, \ldots, e^{-j(I-1)} \right) \]
\[ c(i) = \begin{cases} \frac{2\pi}{T} \cdot \alpha \cdot i^2 & \text{for } i = 0, 1, \ldots, \frac{T}{2} \\ \frac{2\pi}{T} \cdot \alpha \cdot (I - i)^2 & \text{for } i = \frac{T}{2} + 1, \frac{T}{2} + 2, \ldots, I - 1 \end{cases} \]
where \( s = [s(i)] \) is the output vector of the complex smear transform, \( W_I \) is the \( I \times I \) DFT matrix, \( D_I \) is a \( I \times I \) diagonal matrix, and \( A^\dagger \) denotes the conjugated transpose of matrix \( A \), respectively [7].

After the complex smear transform, we calculate a convolution \( d = [d(i)] \) of \( s \) with a highpass filter \( h(n) \). In this work, we employ the following zero-phase filter \( H(z) \):
\[ H(z) = \frac{-z + 2 - z^{-1}}{4} \]
where \( H(z) \) is the \( z \)-transform of filter’s impulse response \( h(n) \). When \( k \) is the watermark message given by the data owner, our watermarking utilizes an impulse signal with nonzero value at the position index \( k \) as a signature. The \( k \)-th sample \( d(k) \) is then represented as
\[ d(k) = \frac{-s(k+1) + 2s(k) - s(k-1)}{I} \]
From \( d(k) \), we derive the optimal impulse signal \( \hat{l} = [l(i)] \in \mathbb{C}^I \) as
\[ \hat{l} = f \cdot \begin{bmatrix} 0 & \cdots & 0 & e^{j \arg(d(k))} & 0 & \cdots & 0 \end{bmatrix}^T \]
where \( f \) is a gain factor to provide a tradeoff functionality between imperceptibility and robustness. Note that the nonzero value is set to as \( e^{j \arg(d(k))} \) for maximizing the norm of the target sample \( d(k) \) with consideration for a maximum value detection in watermarking detecting.

From the optimum signature \( \hat{l} \), we generate an orthogonal polyphase code \( \hat{s} = [\hat{s}(i)] \) as
\[ \hat{s} = \hat{l} \cdot W_L^\dagger \cdot D_I^{-1} \cdot W_I \cdot \hat{l} \]
where the process in Eq. (13) is referred to as the complex desmear transform [7]. After a conversion from the 1-D sequence \( \hat{s} \) to a 2-D data \( Y = [\hat{y}(m', n)] = [\hat{s} (\frac{m}{N} + m')] \) and a complex-to-real conversion from \( Y \) to \( W = [w(m, n)] \in \mathbb{R}^{M \times N} \), where
\[ w(2m', n) = \Re \{\hat{y}(m', n)\} \]
\[ w(2m' + 1, n) = \Im \{\hat{y}(m', n)\} \]
we add the watermark \( W \) into \( r_i \) in Eq. (4) as
\[ \tilde{r}_i = r_i + w \left( \frac{\beta_i}{\pi} M, \frac{\phi_i}{\pi} N \right) \]
results in the stego model in Fig. 1.

### 2.2 Watermark decoding

Fig. 2 illustrates a block diagram of watermark detection from the watermarked model. In the same manner, the vertices \( \tilde{v}_i = [\tilde{x}_i, \tilde{y}_i, \tilde{z}_i] \) \( (i = 0, 1, \ldots, V - 1) \) of the stego mesh model are first aligned in the normalized coordinate system, where \( V \) is a number of vertices. The normalized vertices \( \tilde{v}_i' = [\tilde{x}_i', \tilde{y}_i', \tilde{z}_i'] \) are converted from orthogonal coordinates \( \tilde{v}_i \) to polar coordinates \( p_i = [\tilde{r}_i, \tilde{\theta}_i, \tilde{\phi}_i] \) and mapped a 2-D data \( \tilde{R} = [\tilde{r}(m, n)] \) as
\[ \tilde{r}(m, n) = \frac{1}{|\mathcal{S}_{m,n}|} \sum_{i \in \mathcal{S}_{m,n}} \tilde{r}_i \]
\[ \mathcal{S}_{m,n} = \left\{ i \mid \frac{\pi}{M} m \leq \tilde{\theta}_i < \frac{\pi}{M} (m + 1), \quad \frac{2\pi}{N} n \leq \tilde{\phi}_i < \frac{2\pi}{N} (n + 1) \right\} \]

After a real-to-complex (RC) conversion from \( \tilde{R} \) to \( Y = [\tilde{y}(m', n)] = [\tilde{r}(2m', n) + j\tilde{r}(2m' + 1, n)] \), we reorder the 2-D data \( Y \) to an 1-D sequence \( \tilde{l} = [\tilde{l}(i)] \) as
\[ \tilde{l} \left( \frac{M}{2} n + m' \right) = \tilde{y}(m', n) \]
For \( \hat{I} \), we employ the complex smear transform as

\[
\hat{s} = \frac{1}{J} W^T J^{-1} \cdot W J \cdot \hat{I}
\]

and calculate the convolution \( \hat{d} = [\hat{d}(i)] \) of \( \hat{s} = [\hat{s}(i)] \) with the higpass filter \( h(n) \). For the resulting sequence \( \hat{d} \), maximum value detection is employed for finding the position index \( \hat{k} \) with the maximum value of \( |\hat{d}(i)| \) as

\[
\hat{k} = \arg \max |\hat{d}(i)|
\]

where \( \hat{k} \) is the detected signature. In this paper, if \( \hat{k} \) in (21) is identical to \( k \) in (12), we determine that the correct watermark is detected. This detection process is equivalent to calculating the correlation between the spreading sequence \( \hat{s} \) and the watermarked sequence \( \hat{I} \).

3. Experimental Results and Conclusions

The performance of the proposed watermarking technique is evaluated for a 3-D semi-regular bunny model with 65538 vertices and 131072 cells as shown in Fig. 3(a). In the simulations, we used the following parameters: \( M = N = 16 \) in Eq. (5) and \( \alpha = 30.5 \) in Eq. (9). From \( M \) and \( N \), the payload of the proposed method is \( \log_2 \left( \frac{M^2 \cdot N}{T} \right) = 7 \) [bits]. The watermarked mesh models of the proposed algorithm for some gain factors \( f \) are displayed in Fig. 3(b)-(d).

### Table 1: Ratios [%] of detecting the correct message of the proposed method with various gain factors \( f \)

| Gain factor \( f \)     | 0.005 | 0.01  | 0.02  | 0.04  |
|------------------------|-------|-------|-------|-------|
| Proposed method        | 3.9   | 13.3  | 52.3  | 100   |
| with highpass filtering|       |       |       |       |
| Conventional method    | 1.6   | 3.1   | 10.2  | 19.5  |
| without highpass filtering|    |       |       |       |

To assess the robustness of the watermark, we construct all stego models with the different signature \( k \). The ratios of detecting the correct message are tabulated in Table 1 for the Stanford Bunny model. The experimental results in the table demonstrate the superiority of the proposed watermarking scheme with highpass filtering over the conventional watermarking scheme without highpass filtering. As demonstrated above, a tradeoff between imperceptibility and robustness should be considered through the gain factor \( f \) so that an optimal watermark for each application can be developed.

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