An Algorithm Based on Skeleton Extraction and Inscribed Sphere Analysis for 3D Model Information Hiding

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Abstract

Invisibility, robustness and blindness are three difficult points for 3D model information hiding. In this paper, a new robust and blind information hiding algorithm for 3D models is proposed. Skeleton of 3D models is extracted, and skeleton points are obtained inside the objects at the same time. Taking skeleton points as centers, EMIS are obtained according to Euclidean Maximum Inscribed Sphere (EMIS) in skeleton definition to ensure invisibility and robustness. Setting threshold, get Minimum Inscribed Sphere (MIS) based on EMIS. Keep the radius of MIS be no less than the threshold. Take the parity of MIS earned times as the modification space for information hiding. The Rate of Barycenter and Cross-point (RBC) is used as an auxiliary method to improve robustness and blindness. Experiments prove that this algorithm is of good feasibility, invisibility and robustness against common attacks.

Keywords: Information hiding, Skeleton, Euclidean inscribed sphere, 3D, Blind detection

1. Introduction

Traditional information security transmission technology based on cryptography and secure channel has exposed more limitations [1-2]. Based on different media, information hiding embedded technology has provided more reliable means of secure communication technologies. Increased human visual demand, mature 3D acquisition technology and developed computer geometric modeling have boosted many applications of 3D models. Network has provided high convenience for transmission of 3D models. 3D models, carrying lots of data, are the new favorite of network transmission.

With rapid development, increasing attention is paid to 3D information hiding embedded (IHE) algorithms. But study on 3D IHE is insufficiently. Difficulty of 3D models IHE algorithm is an appropriate balance between robustness and blindness, which is pointed out in [3]. Most of the earlier spatial-domain-based algorithms took vertex coordinates and topological properties to embed data [4-7]. Using affine invariant, as pointed in literature [4-5, 8-15], algorithms based on spatial domain are only robust against affine transformation but fragile to attacks such as noise and topology changes. Transform-domain-based algorithms are few and robust against affine transformation, noise, filtering, even cropping, but not-blind and have applicability restrictions [16-18]. There also exists spatial algorithm based on transform-domain decomposition [19] or blind transform-domain algorithm [20], but it is robust and blind against a few common attacks such as random and affine transformation.

Hence, we propose a definition named Euclidean Maximum Inscribed Sphere (EMIS) according to Euclidean theory [21]. Then we present here a new IHE algorithm based on skeleton and EMIS. By analysis Inscribed sphere-Inscribed cube (ISIC), obtain data hiding area. This algorithm is unrelated with vertex number, coordinate variation and topology modification. Algorithm based on skeleton and EMIS is sensitive to scaling, so we use the Rate of Barycenter and Cross-point (RBC) proposed in [22] as an auxiliary method to perfect robustness of our algorithm. The rest of this paper is organized as follows: Section 2 briefly presents the overview of the basic definition and architecture of 3D model skeleton and Inscribed Sphere Analysis (ISA). Section 3 comprises detailed information of hiding carrier, hiding regulation and process. Section 4 provides detailed information of extraction process.

Finally in Section 5, we demonstrate the robustness and feasibility of this algorithm by experimental results. Then this paper concludes with our comments in Section 6.
2. Skeleton of 3D models

Skeleton is an excellent simplified representation, which can keep the same shape information and topology features as the original models, such as connected district, branch structure and so on.

Concept of 3D skeleton originally proposed by Blum [22-23]: Skeleton of the original model V is comprised of all centers of EMIS. Every EMIS is not contained by any other spheres in V and has at least two points tangent to model boundary.

The above features of skeleton are interpreted as the most centralized energy area of energy theory in information hiding [24]. Hiding information using skeleton can achieve strong robustness and remarkably resist against many attacks such as, rotation, mesh simplification and noise.

3. Inscribed Sphere Analysis

According to definition of EMIS, we propose Inscribed Sphere Analysis (ISA) theory. We get ISA results inside the 3D model according to the order such as EMIS-Inscribed cube-Inscribed sphere-Inscribed cube…….-Inscribed sphere. The analysis process is defined as Inscribed sphere-Inscribed cube (ISIC). Two-dimensional diagram is shown as Figure 1, and three-dimensional diagram is shown as Figure 2.

![Figure 1. ISIC analysis](image1)

(a) 3-dimensional ISIC analysis (b) Inscribed spheres

![Figure 2. 3-dimensional ISIC](image2)

Taking Figure 2 for example, ISIC analysis steps are as follows:

Step 1: Determine the center of EMIS. We obtain a series of skeleton points regarded as the centers of EMIS during the skeleton extraction process.
Step 2: According to 3D model skeleton definition, compute EMIS $S_0$ of every skeleton point.

Step 3: Obtain Inscribed Cube (IC) $C_1$ of $S_0$ by programming.

Step 4: Obtain Inscribed sphere (IS) $S_1$ of $C_1$.

Step 5: Repeat the above ISIC analysis process.

In which, $S_0$ is EMIS of certain skeleton point; obtain IS $S_1$ by three times repeating of analysis.

4. Information Hiding based on EMIS

4.1. Information hiding rules

Choose binary value corresponding to IS analysis time as hiding carrier. There are five rules:

Rule 1: IS analysis is a repetitive process of ISIC until radius of inscribed sphere is less than threshold. Then stop analyzing and abandon the IS with radius less than threshold. Take IS with radius greater than the abandoned one as minimum inscribed sphere (Mini-IS).

Rule 2: Radius of Mini-IS $r_{\min}$ is not less than threshold.

Rule 3: $n$ is obtained time of Mini-IS; analyze $n$ as 0 if $n$ is even, or else analyze $n$ as 1.

Rule 4: Optimize pre-hiding information to achieve maximum consistency with $n$ values of every skeleton point.

Rule 5: If pre-hiding data is opposite to $n$, then change $r_{\min}$ of the skeleton point to make $n$ be same as pre-hiding data; otherwise do not change $n$; and whether reducing or increasing $r_{\min}$ depends on smaller modification quantity.

4.2. Flowchart and steps of information hiding

The algorithm based on ISA is divided into 8 steps, and flowchart is shown in Figure 3.

Figure 3. Hiding procedure based on inscribed spheres analysis

Step 1: Pre-scrambling: using details to compute EMIS radius $r_{\min}$ of the most detailed position in the model and then set threshold $t = r_{\min}$. 

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Step 2: Modify RBC of details of models to repeatedly embed robustness check data \( R \), threshold \( t \), optimal scrambling parameters \( y \) and \( \mu \). And considering every skeleton point as sphere center, obtain EMIS of them.

Step 3: Use threshold \( t \) to analyze EMIS according to rules in section 4.1.

Step 4: Extract information of carrier image by knight tour traversing. Analyze extracted information into binary sequence according to Rule 3. Analytical result is denoted by \( C \), and \( C = (x_1, x_2, ..., x_N) \in \{0, 1\} \).

Step 5: Scramble pre-hiding information by Logistic chaotic mapping, defined as:

\[
y_{n+1} = \mu y_n (1 - y_n), \quad y_n \in (0,1)
\]

Determine parameter \( \mu \) and initial value \( y_0 \) of Logistic chaotic mapping. Set bit sequence of scrambled pre-hiding information is \( C'_n = (b'_1, b'_2, ..., b'_N) \in \{00, 01, 10, 11\} \). And obtain \( C'_n \) by line by line RAID4 traversing from carrier model.

Step 6: Genetic algorithm is applied for optimal adjustment. Suppose \( F \) as the amount of the same bit value in matched positions between \( C'_n \) and \( C \). Optimize \( y_k \) using genetic algorithm to maximize \( F \). The optimization model is expressed as:

\[
F(z) = \max F(y_k) = \max \sum (x_z \oplus y_k)
\]

In which operator \( \oplus \) represents 1 or 0. When both the same it is 1 and is 0 when two bits are different. Obtain optimal solution \( z \) by genetic algorithm.

Step 7: \( z \) is substituted into \( C'_n \) to obtain optimal bit sequence \( C''_n = (b''_1, b''_2, ..., b''_N) \in \{00, 01, 10, 11\} \). Embed RAID4 check data (denoted as \( R' \)), optimal scrambling parameters \( y \) and \( \mu \), threshold \( t \) and pre-hiding information orderly.

Step 8. Analytical value of carrier with embedded information is \( x'_n = x_n + (y_n \oplus x_n) \).

5. Flowchart and steps of information extraction

Information extraction is divided into 5 steps, and flowchart is shown in Figure 4:
Figure 4. Extracting procedure based on inscribed spheres analysis

Step 1: Extract robustness check data $R^L$, threshold $t$, optimal scrambling parameters $\gamma$ and $\mu$ from details of model as auxiliary checking data.

Step 2: Obtain skeleton and skeleton points of model except details.

Step 3: Orderly extract RAID check data $R^L$, threshold $t$, optimal scrambling parameters $\gamma$ and $\mu$ and hidden information from analytical values according to every skeleton point.

Step 4: Discriminate whether fragile sign was distorted. If not, immediately extract information by analysis from other parts. Otherwise, turn to step 5.

Step 5: Compare auxiliary checking data and extracted data from other parts, and recover hiding data.

6. Simulation experiment

Experiments for this algorithm have been taken on several models such as Chinese dragon, Hand-olivier and Ramesses.

6.1. Invisibility

Set change value of $r_{\text{min}}$ is $\pm \Delta$. And radius change amount of EMIS after Inscribed Sphere Inverse Analysis (ISIA) is $\sigma = \pm \Delta \left(\sqrt{2}\right)^{\gamma}$. Obtain stego-model after ISIA. And surface of stego-model is different from carrier model. There are two measures of invisibility.

6.1.1. First measure-human visual imperceptibility

Details enlarged drawings of the original models and stego models shown in Figure 5 illustrate that this algorithm is of good invisibility to satisfy human visual imperceptibility.
6.1.2. Second measure-signal noise rate (SNR)

SNR represents distortion degree between stego models and the original models, shown as:

$$ SNR = \frac{\sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} (r_i - r_i')^2} $$

(3)

Radius signal noise rate (RSNR) of EMIS can measure whether the distortion caused to the stego model is perceptible or not. RSNR can be calculated by:

$$ RSNR = 20 \times \log_{10}(SNR) $$

(4)

In which, $r_i$ is EMIS radius of the original model, $r_i'$ is EMIS radius of stego model, and N is the total number of Euclidean inscribed spheres in the 3D model [22]. RSNR based on this algorithm is averagely 108.27dB.

<table>
<thead>
<tr>
<th>Table 1. RSNR of the proposed algorithm</th>
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<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>RSNR(dB)</td>
</tr>
</tbody>
</table>

6.2. Robustness

The robustness of this algorithm has been tested under different attacks. The robustness is evaluated by BER (bit error rate) [25] of the extracted information bit sequence, as well as the correlation coefficient [26] between the extracted information bit string \{s'\} and the original one \{s\}, as follows:

$$ Corr = \frac{\sum_{i=1}^{N-1} (s'_i - \overline{s})(s_i - \overline{s})}{\sqrt{\sum_{i=1}^{N-1} (s'_i - \overline{s})^2 \cdot \sum_{i=1}^{N-1} (s_i - \overline{s})^2}} $$

(5)

In which $\overline{s}$ and $\overline{s}'$ respectively indicate the averages of the hiding information bit strings \{s'\} and \{s\}.

6.2.1. Robustness against affine transformation and vertex reordering
Figure 6 shows that extracted information under these attacks is of good integrity.

![Figure 6](image)

**Figure 6.** The extracted information under affine transformation and vertex reordering

Experimental data show that the proposed algorithm is 100% robust against similarity transformation such as translation, rotation and so on. Unrelated with vertex order, this algorithm is robust against vertex reordering.

6.2.2. Robustness against other attacks

Extracted information and stego models under other attacks are shown in Figure 7.

![Figure 7](image)

**Figure 7.** The extracted information under other attacks

The average experimental results are shown in Table 2, 3, 4 and 5.

<table>
<thead>
<tr>
<th>Model</th>
<th>Method</th>
<th>BER(%)</th>
<th>Corr(%)</th>
</tr>
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<tbody>
<tr>
<td>Chinese dragon</td>
<td>Ours</td>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Chou[9]</td>
<td>18</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Li [12]</td>
<td>22</td>
<td>66</td>
</tr>
<tr>
<td>Hand-olivier</td>
<td>Ours</td>
<td>4</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Chou[9]</td>
<td>18</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Li [12]</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>Ramesses</td>
<td>Ours</td>
<td>7</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Chou[9]</td>
<td>20</td>
<td>67</td>
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<tr>
<td></td>
<td>Li [12]</td>
<td>19</td>
<td>61</td>
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</tr>
<tr>
<td>Chinese dragon</td>
<td>Ours</td>
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<td>95</td>
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<tr>
<td>Chou[9]</td>
<td>19</td>
<td>74</td>
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<td>Li [12]</td>
<td>37</td>
<td>52</td>
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</tr>
<tr>
<td>Ours</td>
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<td>88</td>
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<tr>
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<td>24</td>
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<tr>
<td>Chou[9]</td>
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<td>Li [12]</td>
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<tr>
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<td>Li [12]</td>
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And results in Table 2, 3, 4 and 5 illustrate that our algorithm is more excellent than other algorithms in robustness against these attacks.

7. Conclusions

In this paper, a new robust 3D information hiding algorithm is proposed. The invisibility is ensured by genetic optimization, Logistic chaotic mapping and appropriate selection of threshold t. Besides, the robustness is due to skeleton extraction, ISA and RBC auxiliary checking. Unrelated with topology information such as vertex and facet, skeleton and ISA ensure the robustness against similarity transformation. But hiding algorithm only based on skeleton and ISA is sensitive to scaling. Taking RBC as auxiliary checking method, this algorithm is robust against scaling. So this IHE algorithm is robust against RST attacks. And this algorithm can resist vertex and facet reordering because extraction process is independent of vertex and facet order. Furthermore, this algorithm can achieve strong robustness against most geometry and connectivity attacks. Experimental results show that the presented algorithm is of superior performance.

8. References

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