Anti-cropping Blind Resynchronization for 3D Watermarking

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Introduction
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Context

3D assets
- Routinely used in movies, video games, and scientific simulations
- Complex, valuable and copyrighted

Piracy threats
- 3D models/ animations leakage
- 3D scanners/ printers

Enduring challenges in 3D watermarking (for traitor tracing)
1. Transforms for 3D mesh: correlated coefficients, causality issues
2. Perceptual modeling: geometry vs. rendering fidelity, complexity
3. Resynchronization: robustness trade-off against cropping / noise addition
4. Security: accessible watermark carriers

Anti-cropping Blind Resynchronization for 3D Watermarking
Radial-based 3D Watermarking

Baseline principle

Encode watermark information in the distribution of radial distances $\rho_i$ between the center of mass $g$ and the vertices $v_i$ [Cho et al., 2007]

Embedding process

1. Compute the radial distances $\rho_i$
2. Compute the histogram $\text{hist}(\rho)$ and the average $\mu_k$ of each bin
3. Compute a target average value $\mu_k \leq \tau_k$ to encode a bit $m_k$ of the watermark payload
4. Modify $v_i$ position so that corresponding bin averages $\mu_k$ matches the target values

Reference implementation

- Quadratic programming framework [Rolland-Nevière et al., 2014]
3D Cropping Attack

Watermark desynchronization

Loss of $g$, $\min(\rho)$, $\max(\rho) \implies$ critical impairment of $\text{hist}(\rho)$

Countermeasures

1. Invariant watermark carrier
   - Sensitivity to noise

2. ( Implicit ) resynchronization
   - Instability, content dependency

3. Pilot sequences (?)

Proposed approach
3D Landmark Vertices

Landmark definition

- \( f: \) vector field \( M \rightarrow \mathbb{R}^2 \)
  - 1. Fitting parametric model of paraboloid to \( \mathcal{N}_2(v) \)
  - 2. Derive RST-resilient 2D vertex signature
- \( Q: \) 2D quantization lattice
- \( q(v) \in Q: \) quantization point closest to \( f(v) \)
- \( v \) is a landmark \( \iff \|f(v) - q(v)\| < \delta \)

Landmark creation

Move vertices \( v_i \in \mathcal{N}_2(v) \) in a local neighborhood to

- Minimize the squared error distortion
- While satisfying the constraint: \( \|f(v) - q(v)\| < \delta \)

Non-interference: non-overlapping neighborhoods for multiple landmarks
Detection of Landmark Vertices

Blind retrieval

1. Fast signature estimation for all vertices (4s for 35k vertices)
2. Detection problem: binary classification (threshold at \( \delta \))

Limitation: false positives due to the low dimension (2D) of the signature

Mitigation strategies

1. Strengthen the landmark constraint, i.e. reduce the threshold \( \delta \)
2. Increase the dimensionality of the signature \( f(\nu) \)
   - Complex neighborhood modeling
   - Nested signatures \( \mathcal{N}_2(\nu) \rightarrow (\mathcal{N}_2(\nu), \mathcal{N}_3(\nu)) \)

\( \alpha \): normalized \( \delta \) w.r.t. \( Q \)
**Center of Mass Recovery**

### Watermark embedding

1. Create a pattern of landmarks to recover \( \mathbf{g} \)
   - Select a non-overlapping set of vertices \( \mathcal{L} \) near a sphere \( S(\mathbf{g}, r) \) (heuristics)
   - Project vertices of \( \mathcal{L} \) onto \( S \)
   - Turn vertices of \( \mathcal{L} \) into landmarks

2. Embed payload with radial 3D watermarking (add constraints to preserve landmarks)

### Watermark extraction

1. Recover the center of mass
   - Retrieve a set \( \hat{\mathcal{L}} \) of candidate landmarks
   - Compute an estimate \( \hat{\mathbf{g}}_{\hat{\mathcal{L}}} \equiv \mathbf{g} \) using robust sphere fitting (RANSAC)

2. Radial 3D watermark extraction using \( \hat{\mathbf{g}}_{\hat{\mathcal{L}}} \) (instead of \( \hat{\mathbf{g}} \))

Low landmark/fitting scores \( \Rightarrow \) automatic resynchronization bypass
Full Resynchronization

**Objective:** transmit \((g, \min(\rho), \max(\rho))\) to fully recover \(\text{hist}(\rho)\)

**Proposal:** embed two synchronization patterns \(S_1(g, r_1)\) and \(S_2(g, r_2)\)

#### Watermark embedder

1. Define two sets of landmarks \((L_1, L_2)\) using alternate quantizers, e.g. QIM
2. Define \((r_1, r_2)\) as preset linear combination of \((\min(\rho), \max(\rho))\)

**Vertex assignment:** 90% payload vs. 10% resynchronization

#### Watermark decoder

1. Recover the geometrical parameters of both synchronization patterns
   - Isolate candidate landmarks for both quantizers used during embedding
   - Compute \(\hat{g}_{L_1}, \hat{g}_{L_2}\) and \(\hat{r}_1, \hat{r}_2\) after RANSAC sphere fitting for both sets of landmarks
2. Radial 3D watermark extraction using \(\hat{g}_{L_1}, \hat{g}_{L_2}, \hat{r}_1, \hat{r}_2\)
   (when confidence is sufficient)
Benchmarked Against Copping

Remarks

- Resynchronization robust to combined rigid transform and cropping (in contrast with `ground truth`)
- Baselines with/without resynchronization equally robust against valumetric attacks, simplification, etc.
**Wrapping Up**

**Conclusion**

1. New resynchronization paradigm illustrated with radial 3D watermarking
2. Significant gain in robustness against cropping
   ... while preserving performances against standalone noise addition

**Research outlook**

1. Robustness against combined cropping-noise attacks
2. Investigate alternate models for local neighborhoods
3. Security of landmark resynchronization (QIM attacks, geometric attacks)
4. Extension to other types of content, e.g. 2D landmarks for still images
Bibliography

An oblivious watermarking for 3-D polygonal meshes using distribution of vertex norms.

Triangle surface mesh watermarking based on a constrained optimization framework.