A hybrid multi-view stereo algorithm for modeling urban scenes

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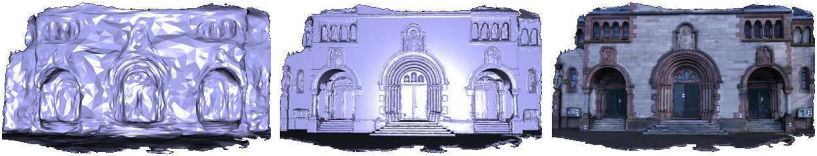

Overview

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1. Introduction: meshes and primitives

2. Hybrid model: 2-step strategy with iterative refinement
   - Step 1: Mesh-based surface segmentation
   - Step 2: Stochastic hybrid reconstruction

3. Experiments

4. Conclusions and future improvements

Introduction

- Urban scenes are difficult to analyze
  - Structures are very different within the same scene...
  - ... but created with man-made rules (piecewise planar, shape repetition)
- Urban scene reconstruction: 2 approaches
  - Meshes
  - 3D primitive arrangements

Introduction: Meshes

- **Meshes**: set of vertices, edges and faces that defines the shape of polyhedral objects
- Several methods for generating a mesh from multi-view stereo images
  - Region growing based methods
  - Fusing a set of depth maps
  - Variational methods
  - 3D Delaunay triangulations

- **Pro**: highly detailed scene reconstruction
- **Cons**:
  - Regular structures not optimally modeled
  - Semantic not taken into account

Introduction: 3D-primitive arrangements

- **3D primitives**: planes, spheres, cylinders, cones and tori
- Exploit the **Manhattan-world assumption**
  - Predominance of three mutually orthogonal directions in the scenes

- **Pro**:
  - particularly well adapted to describe urban environments
  - Semantic taken into account
  - Easy to store and render
- **Cons**: Fail to model fine details and irregular shapes

Solution: hybrid (meshes + primitives) model approach!

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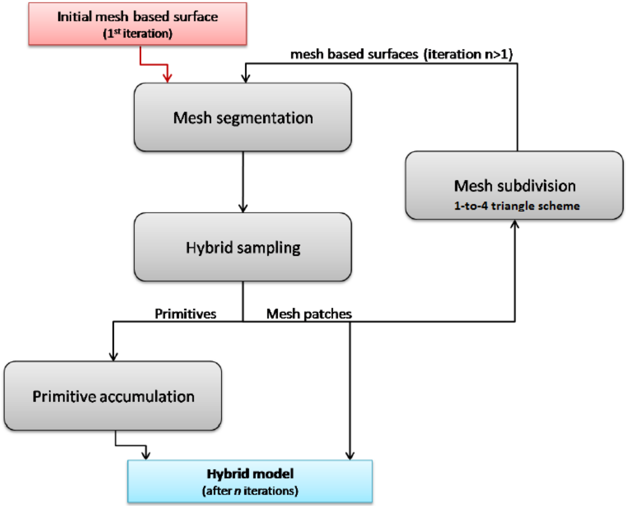
Hybrid model: pipeline



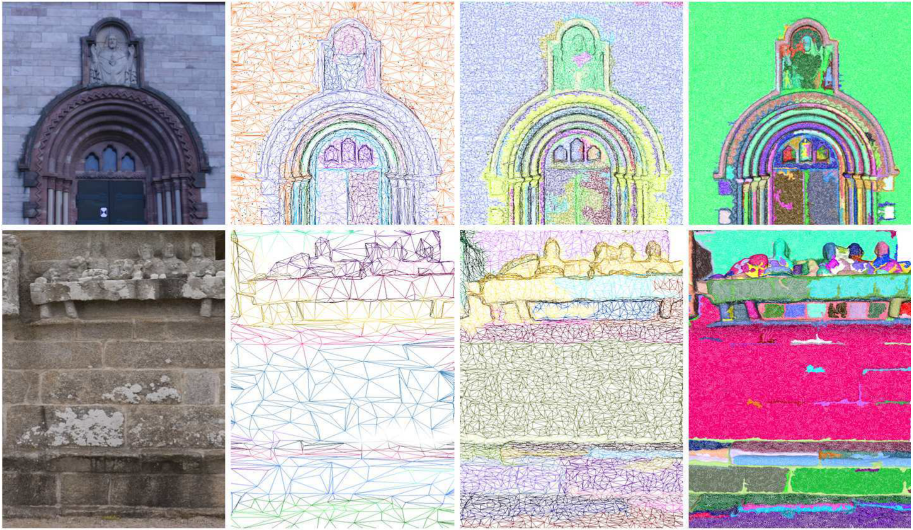
Preliminary segmentation: reduces the complexity of the problem

The procedure stops when the generated facets become too small

Step 1: Mesh-based surface segmentation

- Segmentation problem formulated with a Markov Random Field
  - Vertex set and edge adjacency as in the mesh
- Label for each vertex
  - Planar, developable convex, developable concave, non developable
- Quality of a label configuration: energy
  - Energy given by curvature distributions, label homogeneity and edge preservation
- Subdivision into clusters (using label as discriminant)

Step 1: Mesh-based surface segmentation



Step 2: Stochastic hybrid reconstruction

- H: configuration space of the hybrid models given the segmented initial mesh-based surface $\mathbf{x}^{(0)}$
- $U(\mathbf{x})$: energy measuring the quality of a hybrid model $\mathbf{x} \in H$
- Optimal hybrid model: $\hat{\mathbf{x}} = \arg\min_{\mathbf{x} \in H} U(\mathbf{x})$
- Multi-object energy model:

$$U(\mathbf{x}) = \sum_{i=1}^{N} U_{pc}(x_i) + \beta_1 \sum_{i=1}^{N_m} U_s(m_i) + \beta_2 \sum_{i \bowtie i'} U_a(p_i, p_{i'})$$

with m_i, p_i meshes respectively primitives in $\mathbf{x}$ and $N_m + N_p = N$

Step 2: Photo-consistency U_{pc}

$$U(\mathbf{x}) = \sum_{i=1}^{N} U_{pc}(x_i) + \beta_1 \sum_{i=1}^{N_m} U_s(m_i) + \beta_2 \sum_{i \bowtie i'} U_a(p_i, p_{i'})$$

U_{pc} is the image back-projection error with respect to the object surface

$$U_{pc}(x_i) = A(x_i) \sum_{\tau,\tau'} \int_{\Omega^S_{\tau,\tau'}} f(I_\tau, I^S_{\tau,\tau'})(s)ds$$

with $A(x_i)$ a function tuning the occurrence of primitives/meshes

Step 2: Mesh smoothness U_s

$$U(\mathbf{x}) = \sum_{i=1}^{N} U_{pc}(x_i) + \beta_1 \sum_{i=1}^{N_m} U_s(m_i) + \beta_2 \sum_{i \bowtie i'} U_a(p_i, p_{i'})$$

U_s allows the regularization of mesh patches and penalizes strong bending using the thin plate energy E_{TP}

$$U_s(m_i) = \sum_{\nu \in V_{m_i}} E_{TP}(\nu, \{\bar{\nu}\})$$

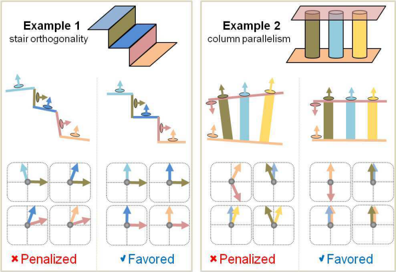
with $\{\bar{\nu}\}$ the set of adjacent vertices to the vertex ν

$$U(\mathbf{x}) = \sum_{i=1}^{N} U_{pc}(x_i) + \beta_1 \sum_{i=1}^{N_m} U_s(m_i) + \beta_2 \sum_{i \bowtie i'} U_a(p_i, p_{i'})$$

U_a favors both perpendicular and parallel primitive layouts and object repetition in a scene

$$U_a(p_i, p_{i'}) = \omega_{ii'}(1 - cos(2\gamma_{ii'})^{2\alpha})$$

with $\gamma_{ii'}$ the angle between the direction of revolution of the two primitives and $\omega_{ii'}$ weight which favors repetitiveness



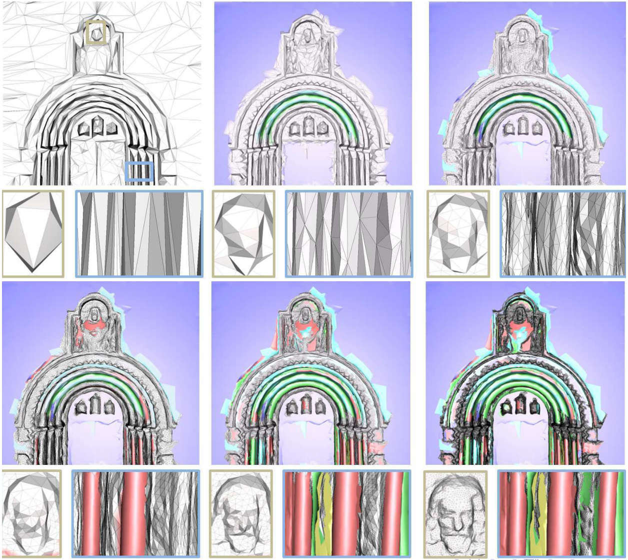
Step 2: Jump-Diffusion based sampling

$$U(\mathbf{x}) = \sum_{i=1}^{N} U_{pc}(x_i) + \beta_1 \sum_{i=1}^{N_m} U_s(m_i) + \beta_2 \sum_{i \bowtie i'} U_a(p_i, p_{i'})$$

- Can sample from two different types of structures
- **Jump dynamics**: $\min(1, \frac{Q(\mathbf{y} \to \mathbf{x})}{Q(\mathbf{x} \to \mathbf{y})} e^{-\frac{U(\mathbf{y}) - U(\mathbf{x})}{T}})$
  - Convergence necessary condition: jump must be reversible
- **Diffusion dynamics**: $d\mathbf{x}(t) = -\frac{dU(\mathbf{x})}{d\mathbf{x}} dt + \sqrt{2T(t)} d\omega_t$
  - $T \gg 0$: local minima avoided
  - $T \simeq 0$: diffusion dynamics act as a gradient descent
  - Mesh adaptation: $\nabla_{m_i} U = \nabla_{m_i} U_{pc} + \beta_1 \nabla_{m_i} U_s$
  - Primitive adaptation: $\nabla_{\theta_i} U = \nabla_{\theta_i} U_{pc} + \beta_2 \sum_{i'} \nabla_{\theta_i} U_a$

Hybrid model: iterative refinement

It allows the extraction of the main regular structures at low resolutions



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Experiments

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Conclusions and future improvements

- Original multi-view reconstruction algorithm (primitives for regular structures, mesh patches for irregular components)
- High storage savings but accuracy similar to the best mesh-based algorithms
- Takes into account semantic knowledge (some occlusions can be solved)
- Jump-Diffusion sampler explores complex configuration spaces fast

- **Possible improvements**:
  - More constraints on structure repetition (shape layout prior)
  - Extension of primitives set (with automatically adaptation to the scene)
  - Embedding segmentation step into sampling procedure

Thanks for your attention!

Questions?