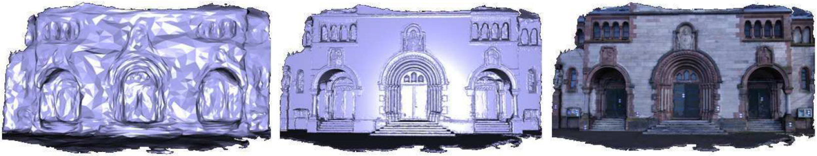
A hybrid multi-view stereo algorithm for modeling urban scenes

Sasha Pagani, Julia Giger, Prashanth Chandran

Swiss Federal Institute of Technology

April 24, 2017



Overview

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

Overview

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

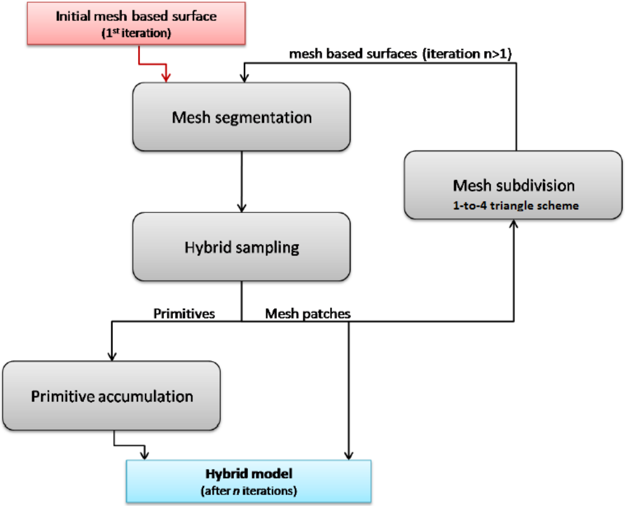
- **3D primitives**: planes, spheres, cylinders, cones and tori
- Exploit the **Manhattan-world assumption**
  - Predominance of three mutually orthogonal directions in the scenes

- **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!

Overview

Hybrid model: pipeline

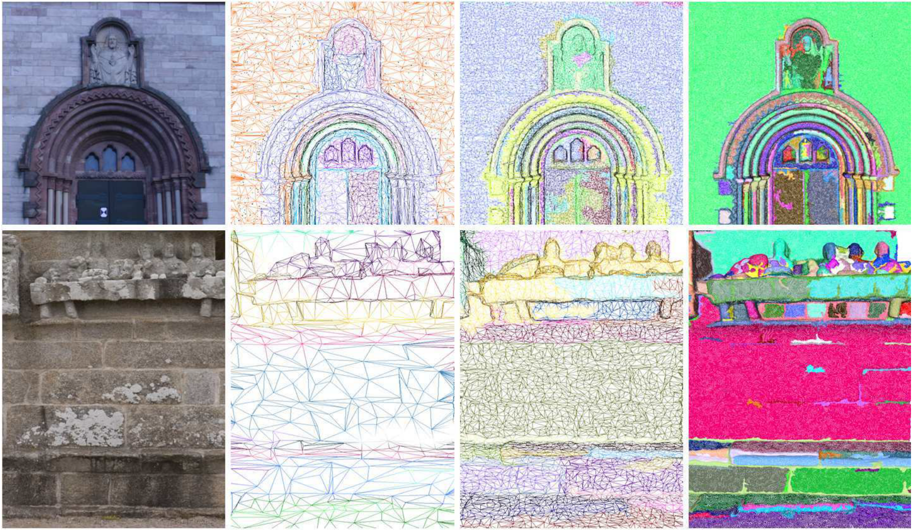


Preliminary segmentation: reduces the complexity of the problem
The procedure stops when the generated facets become too small

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: $\hat{\mathbf{x}} = \underset{\mathbf{x} \in H}{\arg\min}\ U(\mathbf{x})$
- 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

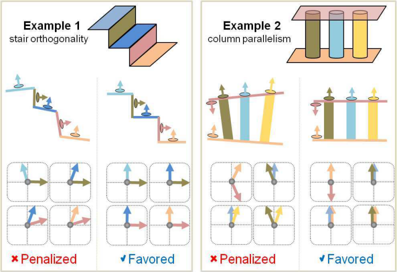
Step 2: Priors on shape layout U_a

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

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



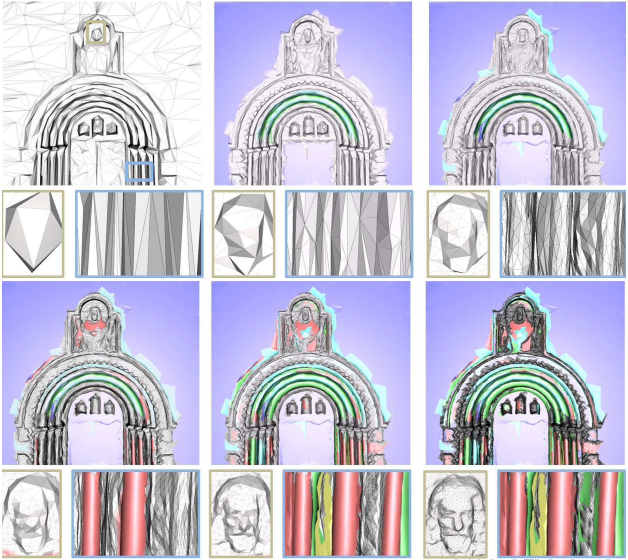
Step 2: Jump-Diffusion based sampling

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

- Can sample from two different types of structures
- **Jump dynamics**: $\min(1, \frac{Q(\mathbf{y} \to \mathbf{x})}{Q(\mathbf{x} \to \mathbf{y})} e^{-\frac{U(\mathbf{y}) - U(\mathbf{x})}{T}})$
  - Performs a switch on the type of an object
  - Convergence necessary condition: jump must be reversible
- **Diffusion dynamics**: $d\mathbf{x}(t) = -\frac{dU(\mathbf{x})}{d\mathbf{x}} dt + \sqrt{2T(t)} d\omega_t$
  - Optimizes the parameters for the chosen object
  - $T \gg 0$: 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

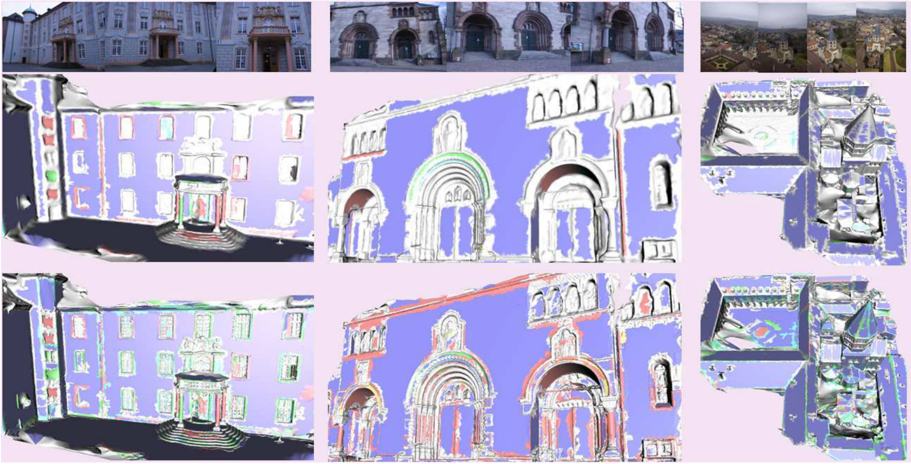
It allows the extraction of the main regular structures at low resolutions



Overview

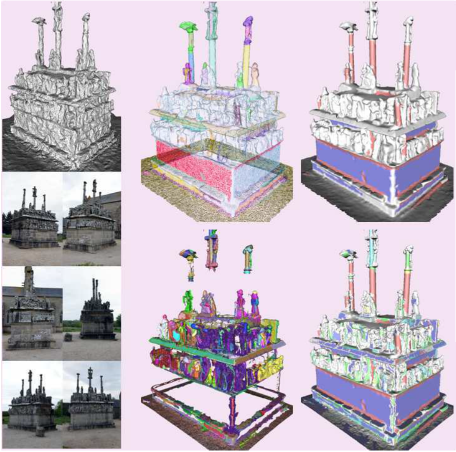
Experiments

Entry-P10 | Herz-Jesu-P25 | Church



Experiments

Calvary



	initial surface	LR hybrid model	HR hybrid model
Entry-P10 (10 images)	$9K$ vert. $16K$ fac.	51 prim. $20K$ vert. $37K$ fac.	342 prim. $0.33M$ vert. $0.62M$ fac.
Calvary (27 images)	$23K$vert. $47K$ fac.	37 prim. $56K$ vert. $0.11M$ fac.	426 prim. $0.55M$ vert. $1.04M$ fac.
Herz-Jesu-P25 (25 images)	$14K$ vert. $17K$ fac.	41 prim. $42K$ vert. $77K$ fac.	263 prim. $0.38M$ vert. $0.74M$ fac.
Church (37 images)	$21K$ vert. $34K$ fac.	143prim. $82K$ vert. $0.15M$ fac.	406 prim. $0.13M$ vert. $0.22M$ fac.

Experiments: Observations

- Segmentation stage: defines the partitions of the initial surface to sample $\rightarrow$ not crucial
- Hybrid sampling re-meshes patches which aren't relevant enough
- Tromp l'oeil structures correctly reconstructed
- Partially occluded regular structures more accurately reconstructed
- Reduction of storage capacity for similar accuracy
- Better preservation of the details
- Some details located inside the main structures can be lost depending on the tuning parameter for the photo-consistency

Overview

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?