Grammar-based Machine Learning for Automatic 3D BIM Reconstructions

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1. Motivation
2. Indoors Building Information Modeling
3. Facade Grammar and Facade Reconstruction
4. Pilot Studies - Grammars & Automated BIM
5. Results
6. Conclusions and Outlook
1. Motivation – ASCII-like 3D City Model Refinements (outdoors and indoors)

- Detailed facade models (BIM LoD3)
  - Explicit facade geometry
  - Semantic information

- New Applications (BIM LoD4)
  - Computer graphics, virtual reality
  - Detailed urban planning
  - 3D navigation
  - Environmental simulations
  - Energetic calculations
  - Finite Elemental Analysis
  - Building Information Models (BIM)
  - …
2. Indoors BIM Modeling
Based on Input Data (given, image-based, range-based)

- Using available architectural drawings or 2D plans
  - Promising results
  - Subject to change
  - Not always accessible to public

Dosch et al., 2000

Peter et al., 2013
3. Grammars & BIM Facade Reconstructions

The Machine Learning Algorithm

- Cell decomposition
  - Extraction and modeling of facade structures using point clouds (LiDAR or Imagery)

- Knowledge inference
  - Detection of recurrent features and structures
  - Rule derivations

- Knowledge propagation
  - Hypotheses for verification and make-up
  - Synthetic facade structures

Cell decomposition

Knowledge inference

Knowledge propagation

Data driven

Model driven

Facade grammar
3. The Facade Grammar

- For the refinement of LOD2 building models
- Based on:
  - Lindenmayer systems (conditions, context, probabilities)
  - Split grammar (tessellation of the facade in disjunct elements)
- Individual facade grammars can be automatically derived

- $G^{Facade}(V,T,P,F)$:
  - $V$ ... Non-terminals
  - $T$ ... Terminals
  - $F$ ... Axiom
  - $P$ ... Production rules
    - Split rules
      - $(F \rightarrow W^*, \ W \rightarrow WGW)$
    - Instantiation rules

- Geometry tile $G, g_i$
- Wall tile $W, w_i$
3. The Façade Grammar - Searching for Terminals

Knowledge Inference

• Spatial Partitioning
  • Segment the facade into floors by horizontal partition planes
3. The Façade Grammar - Searching for Terminals

Knowledge Inference

• Spatial Partitioning
  • Segment the facade into floors by horizontal partition planes
  • Divide each floor into tiles by vertical splits along the geometry borders
3. The Façade Grammar - Searching for Terminals

**Knowledge Inference**

- **Spatial Partitioning**
  - Segment the facade into floors by horizontal partition planes
  - Divide each floor into tiles by vertical splits along the geometry borders
  - *Wall tiles, geometry tiles*
  - Classification of the tiles
4. Pilot Studies - BIM Facade Application
4. Pilot Studies – BIM Façade Data Collection

- Facade is covered by imagery collected from 32 stations.
- At each station 3 images were collected
- Time for data collection <15min
4. Pilot Studies – BIM Facade Results (LoD3)

image-based 3D point cloud (close-range photogrammetry)

Rotebühlbau, Stuttgart
4. Pilot Studies – BIM Indoors (LoD4)

VGI and Grammar for 3D BIM

• Application scenario:
  • Generate **hypotheses for indoor geometries for the 2nd floor** of the CS building (Uni Stuttgart) using **erroneous and incomplete trajectories and grammars**

  ▪ Input Data
    ▪ **Trajectories**: 250 odometer tracks within the 2nd floor
    ▪ **Grammar**: high-level grammar automatically derived from a floor plan of the 1st floor
    ▪ **3D building hull**: LOD2 Model of Stuttgart City Surveying office
4. Pilot Studies – BIM Indoors (LoD4)

Grammar Application - Results

- Procedural modeling processes
  - Generation of weak floor segments (Axiom)
  - Application of a **L-System** onto the Axiom
  - Application of a **Split- Grammar** onto non-floor segments
- Comparison with reality (131 rooms)
  - **Pure data-driven**: 29 rooms
  - **Split Grammar appl. onto data-driven Floors**: 92 rooms
  - **Split Grammatik appl. onto completed floors L-System**: 116 rooms
- Average error of the room width: ~2m
4. Pilot Studies – BIM Indoors Grammar

L-System for Modeling Hallways

• Production rules

- \( \omega: R(\text{ACTIVE})?I(\theta_{\text{in}}, \text{UNASSIGNED}) \)
- \( p_1: R(\text{mode}) > ?I(\theta, \text{state}): \text{state}==\text{SUCCEED} \& \& \text{mode}==\text{ACTIVE} \)
  
  \[
  \begin{align*}
  \text{LayoutSetting}(\theta, \text{mode}) \text{ sets } \theta_i[0-4] \rightarrow +(\theta, \text{angle})F(\theta, \text{len}) \\
  B^h(\text{ACTIVE}, \theta_p[1]) B^h(\text{ACTIVE}, \theta_p[2]) B^v(\text{INACTIVE}, \theta_p[3]) \\
  B^v(\text{INACTIVE}, \theta_p[4]) R(\text{ACTIVE})?I(\theta_p[0], \text{UNASSIGNED})
  \end{align*}
  \]
- \( p_2: R(\text{mode}) > ?I(\theta, \text{state}): \text{state}==\text{FAILED} \rightarrow \varepsilon \)
- \( p_3: B^h(\text{mode}, \theta): \text{mode}==\text{ACTIVE} \rightarrow [R(\text{mode})?I(\theta, \text{UNASSIGNED})] \)
- \( p_4: ?I(\theta, \text{state}): \text{state}==\text{UNASSIGNED} \)
  
  \[
  \begin{align*}
  \text{ConsistencyConstraints}(\theta) \text{ adjusts } \text{state}, \theta \rightarrow ?I(\theta, \text{state})
  \end{align*}
  \]
- \( p_5: ?I(\theta, \text{state}): \text{state}!==\text{UNASSIGNED} \rightarrow \varepsilon \)
- \( p_6: B^v(\text{mode}, \theta): \text{mode}==\text{INACTIVE} \)
  
  \[
  \begin{align*}
  \text{ActivationControl}(\text{sets mode}) \rightarrow B^v(\text{mode}, \theta)
  \end{align*}
  \]
- \( p_7: B^v(\text{mode}, \theta): \text{state}==\text{SUCCEED} \& \& \text{mode}==\text{ACTIVE} \)
  
  \[
  \begin{align*}
  \rightarrow [Q(\text{mode})?I(\theta, \text{UNASSIGNED})]
  \end{align*}
  \]
- \( p_8: Q(\text{mode}) > ?I(\theta, \text{state}): \text{state}==\text{SUCCEED} \& \& \text{mode}==\text{ACTIVE} \)
  
  \[
  \begin{align*}
  \text{LayoutSetting}(\theta, \text{mode}) \text{ sets } \theta_i[0-3] \rightarrow +(\theta, \text{angle})U(\theta, \text{len}) \\
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  R(\text{ACTIVE})?I(\theta_p[0], \text{UNASSIGNED})
  \end{align*}
  \]
- \( p_9: Q(\text{mode}) > ?I(\theta, \text{state}): \text{state}==\text{FAILED} \rightarrow \varepsilon \)
4. Pilot Studies - Iterative Learning and Verification

Results

• Seamless transition from LOD3 to LOD4

  ▪ Grammar update:

    ▪ Enhanced split grammar

    **Enhanced split grammar:**

    - \( R_a^{Single} : Space \rightarrow Split^{Space}(n_a \mid d_a) \)
    - \( R_b^{Single} : Space \rightarrow Split^{Space}(n_b \mid d_b) \)
    - \( R_c^{Single} : Space \rightarrow Split^{Space}(n_c \mid d_c) \)
    - \( R_d^{Single} : Space \rightarrow Split^{Space}(n_d \mid d_d) \)
    - \( R_e^{Single} : Space \rightarrow Split^{Space}(n_e \mid d_e) \)

    ▪ \( R_{bc}^{String} : Space \rightarrow Split_c^{Space} \odot \square \)

    ▪ \( R_{cb}^{String} : Space \rightarrow Split_b^{Space} \odot \square \)

• Verification of 3D model

Susanne Becker
4. Pilot Studies - Iterative Learning and Verification

Results

• Seamless transition from LOD3 to LOD4
  - Grammar application:

 Susanne Becker
5. Conclusions and Outlook

Grammar was proven by the Pilots and 2 DFG ResearchProjects (just completed) – excellent reviews!

- Automatic approach for the reconstruction of complete 3D facade and BIM models from dense point clouds is working!
  - Point cloud generation using range and image data collections
  - Automatic inference of individual grammars representing building-specific characteristics
  - Generation of realistic building structures even in areas with inaccurate, noisy or incomplete sensor data
  - Synthetic facade structures for facades not covered by any sensor data
- Extension and abstraction of the building scenario to city models
  - Hierarchical graph-based modeling structure for urban environments
  - Network of geometrical and topological relationships
    - facilitates the analysis and preservation of geometrical consistency
    - allows for the derivation and modelling of higher-order dependencies

High R&D potential in grammar-based modeling of geometric and semantic building information
5. Conclusions and Outlook – R&D Potential

Hierarchical Graph-based Structure for BIM and Urban Environments