3D Building Reconstruction from Monocular Remote Sensing Images

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Background

• An important research problem and an economic solution to large-scale city modeling, compared with using LiDAR data or multi-view imagery.

• Challenges of monocular 3D building reconstruction:
  • The partial invisibility of building footprints and facades
  • The serious shadow effect
  • The extreme variance of building height in large-scale areas
Related Work

Building footprint extraction
- Regarding different parts of a building instance as a unified entirety.
- Achieving satisfying results for low-rise buildings.
- Producing poor segmentation boundaries when extracting high-rise buildings from oblique images.

Building height estimation and 3D reconstruction
- Most existing methods focus on height estimation from near-nadir images.
- A recent study proposed a method for building height estimation from oblique images.
- It only focus on the single-task height estimation instead of 3D reconstruction.
Methods: Task definition of MTBR-Net

- **Roof and Facade** have complete contours on the monocular remote sensing images.
- **Footprint** is partially invisible but has the same shape as the corresponding roof.
- **Building Skeleton** includes 4 semantic edges of a 3D building model.
- **Skeleton Orientation** is designed for converting the raster map into vector 3D model.

- **Offset Field A** is defined as 2 pixel-wise values \((x, y)\) located in roof and facade regions.
- **Offset Field B** is defined as 2 pixel-wise values \((x, y)\) located in footprint regions.
- **Offset Angle** is an absolute value for each image.
Methods: Training of MTBR-Net

- **The four semantic-related tasks** are all formulated as pixel-wise classification problems and trained with the cross entropy loss.
- **The two offset field prediction tasks** are defined as pixel-wise regression tasks, of which the loss is calculated by the endpoint error (EPE).
- **The image-wise offset angle prediction task** is trained with the cross entropy loss.
- The total loss of the seven tasks is the weighted sum of each task-specific loss.

\[
L_{seg} = -\frac{1}{N} \sum_{i=1}^{N} \sum_{c=1}^{C} y_{i,c} \times \log(p(y_{i,c}))
\]

\[
L_{field} = \frac{1}{N} \sum_{i=1}^{N} ||\vec{\Omega}_{i}^{pred} - \vec{\Omega}_{i}^{gt}||_2
\]
Methods: Optimization of the 3D building model

- **Height vector optimization**: a prior knowledge based template matching method for optimizing the height estimation results.
- **Polygonization**: a skeleton orientation based method for converting the raster results into vector 3D building model with valid shapes.
Results: Height estimation performance

Table 1. Comparison of building height estimation on our proposed dataset. We report the EPE of the roof instances within different height range and the average EPE of all instances. Our method reduces the EPE of high-rise buildings by 5 to 24 pixels compared with [7].

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Method</th>
<th>EPE of different height range (in pixels)</th>
<th>Average EPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0-10</td>
<td>10-20</td>
</tr>
<tr>
<td></td>
<td>Ours</td>
<td>4.92</td>
<td>4.24</td>
</tr>
<tr>
<td></td>
<td>Ours</td>
<td>6.63</td>
<td>9.96</td>
</tr>
</tbody>
</table>

Table 2. Comparison of building height estimation on DFC19 dataset, in terms of the MAE and RMSE of actual height (in meters), EPE of offset vector (in pixels), and angle error (in degrees).

<table>
<thead>
<tr>
<th>Method</th>
<th>Actual Height</th>
<th>Offset EPE</th>
<th>Angle Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAE</td>
<td>RMSE</td>
<td>Roof</td>
</tr>
<tr>
<td>Kunwar [16]</td>
<td>8.33</td>
<td>19.65</td>
<td>-</td>
</tr>
<tr>
<td>Zheng et al. [34]</td>
<td>8.72</td>
<td>19.32</td>
<td>-</td>
</tr>
<tr>
<td>Christie et al. [7]</td>
<td>7.73</td>
<td>16.87</td>
<td>5.44</td>
</tr>
<tr>
<td>Ours</td>
<td><strong>4.75</strong></td>
<td><strong>9.57</strong></td>
<td><strong>4.67</strong></td>
</tr>
</tbody>
</table>

The proposed dataset will be released on https://liweijia.github.io/projects/building_3d/.
Results: Building segmentation performance

<table>
<thead>
<tr>
<th>Method</th>
<th>In-domain dataset (Roof)</th>
<th>In-domain dataset (Footprint)</th>
<th>Out-domain dataset (Roof)</th>
<th>Out-domain dataset (Footprint)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Precision</td>
<td>Recall</td>
<td>F1-score</td>
<td>Precision</td>
</tr>
<tr>
<td>Cascade Mask R-CNN [4]</td>
<td>66.68</td>
<td>67.06</td>
<td>66.87</td>
<td>61.27</td>
</tr>
<tr>
<td>Mask R-CNN [13]</td>
<td>67.98</td>
<td>69.35</td>
<td>68.66</td>
<td>63.43</td>
</tr>
<tr>
<td>PANet [21]</td>
<td>68.38</td>
<td>67.98</td>
<td>68.18</td>
<td>64.03</td>
</tr>
<tr>
<td>HR-Net [30]</td>
<td>68.78</td>
<td>66.09</td>
<td>67.41</td>
<td>64.19</td>
</tr>
<tr>
<td>Li et al. [18]</td>
<td>71.76</td>
<td>69.25</td>
<td>70.48</td>
<td>65.71</td>
</tr>
<tr>
<td>Ours (w/o optimization)</td>
<td>72.72</td>
<td>71.37</td>
<td>72.04</td>
<td>66.85</td>
</tr>
<tr>
<td>Ours (w/ optimization)</td>
<td>72.72</td>
<td>71.37</td>
<td>72.04</td>
<td>69.47</td>
</tr>
</tbody>
</table>

- We compare the segmentation performance of our approach with the current SOTA and 4 other competitive segmentation methods.
- Our method improves the F1-score of SOTA by 2.5% and 4.3% for footprint extraction, indicating the effectiveness of warping the predicted roof instances to footprints using the offset vectors.
Conclusions

• We have presented a novel 3D building reconstruction method that produces vector 3D building model with accurate roof, facade, footprint, and height,
• Qualitative and quantitative evaluations demonstrate the significant performance gain over current state-of-the-art.
• To the best of our knowledge, this is the first work that produces vector 3D building model reconstruction results from monocular remote sensing images using deep neural networks.
• We believe that this paper provides effective solutions for 3D building reconstruction in large-scale and complex application scenes.
Thank you!