360-Degree 3D Ground Surface Reconstruction Using a Single Rotating Camera

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Introduction

• Backgrounds
  – 360-degree surrounding ground surfaces.
    • Required for heavy machineries in construction sites.

• Related works

Catadioptric stereo camera [18]

Laser scanner


• Hard to calibrate
• Expensive
Objective

To **robustly and precisely** reconstruct a 360-degree 3D ground surface from the images captured by a **single rotating camera**.

**Single rotating camera**: easy to calibrate, low cost.

**Robust and precise Reconstruction**: via effective combination of feature-based and pixel-based methods.
Overview

Robust initial surface estimation by fitting to 3D points of SfM

Surface fitted to 3D Points

Ground coordinate system

Surface refinement by minimizing variances of pixels

Refined surface
Robust initial surface estimation by fitting to 3D points of SfM

Regular mesh

Ground coordinate system

Surface fitted to 3D Points

(1) Structure from motion (SfM).

Estimated camera positions

Estimated 3D points

(2) Scale estimation & mesh arrangement.

ground coordinate system

circle fitted

x-y plane

(3) Initial surface generation by fitting to 3D points.

Surface fitted to 3D points
Overview

Robust initial surface estimation by fitting to 3D points of SfM

Surface refinement by minimizing variances of pixels

Surface fitted to 3D Points

Ground coordinate system

Refined surface
Surface refinement

The heights of each vertex

Cost function: \( C_P(z) = C_{PD}(z) + \alpha_{PS} C_{PS}(z) \)

Data term: \( C_{PD}(z) = \sum_{x_s'} \left( \frac{1}{|n_s|} \sum_{n_s} (I_{n_s}[p_{n_s}(x_s(x_s',z))] - \bar{I}_{n_s}(z))^2 \right) \)

Data term: \( C_{PD}(z) = \sum_{x_s'} \left( \frac{1}{|n_s|} \sum_{n_s} (I_{n_s}[p_{n_s}(x_s(x_s',z))] - \bar{I}_{n_s}(z))^2 \right) \)

Smoothness term

The variance of the pixel values

\( x_s' : \) Sample point on \( x-y \) plane  
\( x_s : \) Point on surface  
\( p_{n_s} : \) Point on image  
\( I_{n_s} : \) Image which observes \( x_s \)  
\( \bar{I}_{n_s}(z) : \) Average of the pixel values  
\( |n_s| : \) Number of the image \( I_{n_s} \)
Outlier removal

Detect outlier pixels of the surface point $x_s$ by taking the median value $\text{MED}(I_{ns})$

$$|I_{ns}[p_{ns}(x_s(z))] - \text{MED}(I_{ns})| > \tau \text{ (threshold)} \quad I_{ns} \text{ is outlier pixel}$$

Minimize the cost function $C_{PS}(z)$ using only inlier pixels
Implementation Details

Pre-defined sample points

- Defined on the x-y plane using pixel-interval
- Dense in near, sparse in far.

Hierarchical meshing

(In 4 or 5 pyramid levels)
Experimental results: Synthetic images

Setting

- The camera rotated 10 degrees per frame capturing 36 images
Estimated surfaces

16m

16m

Ground truth surface

Initial surface (SfM + surface fitting)

SfM + PMVS [5] + surface fitting

Final (proposed method)

Error maps

Initial surface (SfM + surface fitting)

SfM + PMVS [5] + surface fitting

Final (proposed method)

Ground truth surface

0  Z error  10cm
RMSE in distances

<table>
<thead>
<tr>
<th>Distance from the rotation axis</th>
<th>Initial</th>
<th>PMVS</th>
<th>Final (Proposed)</th>
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<tbody>
<tr>
<td>2～4m</td>
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<tr>
<td>4～6m</td>
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<td>8～10m</td>
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<td>10m～</td>
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</tbody>
</table>
Real scene ①

Setting

- The camera rotated 10 degrees per frame capturing 36 images

Scene

Input image (640 × 480 pixels)
Real scene ①: Estimated surface

Result of 3D ground surface generation
(Grid size: 12.5cm)

Textured surface
Real scene ②

Input image (640 × 480 pixels)
Real scene ②: Comparison

Without outlier removal (surface)

With outlier removal (surface)

With outlier removal (surface + texture)
Conclusion

• 360-Degree 3D Ground Surface Reconstruction Using a Single Rotating Camera
  – Propose the method for robustly and precisely reconstructing a 3D ground surface
  – Improve the stability by outlier pixels removal

• Future work
  – Acceleration by optimizing implementation