Real-time Image-based Reconstruction of Pipes Using Omnidirectional Cameras

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In cooperation with
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Motivation

Quelle: http://www.kanalinspekteure.de

Quelle: http://www.ibak.de
Sewer inspection systems

- Inspection of sewer shafts and pipes with mobile camera systems
- Manual evaluation of videos by expert

Task: Create 3d reconstruction for visualization and measuring
Contents

- Image Acquisition and Structure from Motion
- Our reconstruction approach
  - Cylinder mapping
  - Global geometric correction
  - Profile fitting and model creation
- Tests and applications
- Conclusion
Image acquisition for sewer pipe inspection

- Pull cameras out on cable with 35 cm/sec
- Capture images every 5 cm
- Vertical profiles
- Mobile system with cameras
Image acquisition for sewer shaft inspection

- Pull camera up on cable with 35 cm/sec
- Capture image every 5 cm
Spherical camera model

- max. angle
- radius
- principal point
Structure from Motion

Initialization

2d/2d correspondence

\( C_0 \)

\( C_1 \)

\( X_0 \)

\( X_1 \)

\( X \)

\( \text{camera distance 5 cm} \)
Structure from Motion

Tracking

\[ \begin{align*}
X_0 & \quad 2d/2d \text{ correspondence} \\
C_0 & \\
X_1 & \quad \text{camera distance 5 cm} \\
C_1 & \\
X_2 & \quad 2d/2d \text{ correspondence} \\
C_2 & \\
\end{align*} \]
3d reconstruction - Problems and challenges

- Challenging lighting conditions and depth of view
- Strong image distortions
- Brief feature point visibility, large frame-to-frame translation
- Inaccurate camera calibration
- Demands for real-time processing: min. 7 Hz
Our approach

- Image Acquisition and Structure from Motion
- Our reconstruction approach
  - Cylinder mapping
  - Global geometric correction
  - Profile fitting and model creation
- Tests and applications
- Conclusion
Overview of our approach

1. Image preprocessing
   - rotation compensation
   - and cylinder mapping

2. Feature point detection and tracking
   - apply KLT tracker

3. Structure from Motion
   - compute camera poses and 3d geometry

4. Global optimization
   - correct camera path and 3d geometry

5. Measuring
   - classify profiles, create 3d model

- camera poses
- 3d point cloud
- profiles
- 3d model

- camera image
- rotation sensor
1. Image preprocessing: Roll rotation compensation
1. Image preprocessing: Cylinder mapping

- Fisheye camera image
- Aligned cylinder image
- Principal point
2. Feature point tracking

- **Initialization**: Detect KLT feature points
- Find correspondences along image rows
- Create row-dependent horizontal translation function

![Diagram showing feature point tracking with search window and translation graph]
2. Feature point tracking

- **Tracking:** Predict new position with translation function
- Use small search window around target position
- Update horizontal translation function

![Image of frames and search window](image-url)
3. Structure from Motion

Output:

- Computed 3d point cloud
- Computed **camera poses** for each frame (position + rotation)
- Robust estimation using RANSAC
4. Global optimization

- Error accumulation
- Inaccurate camera calibration
  - Bent and conical 3d reconstruction
  - Global optimization needed
  - Bundle Adjustment not useful for real-time application
4. Global optimization

- Correct 3d reconstruction using geometric constraints:

  - **Average camera path** is known
    (vector of gravity = z-axis)
  - Camera baseline between frames is known (approx. 5 cm)
4. Global optimization

- Fit polynomial $P(t)$ to **average camera path**
- Transform 3d points and **camera poses** via mapping of $P(t)$ onto corrected path $P^*(t) = 5 \text{ cm} \cdot t \cdot e_z$

average camera path $P(t)$

camera baseline = 5 cm

distorted reconstruction

corrected reconstruction

z-axis $e_z$
(vector of gravity)
5. Measuring profile shapes

- Classification of horizontal shaft / vertical pipe profiles
- Robust shape estimation from 3d points within slice
5. Creating 3d models for visualization

- Classify profile shapes in 3d points
- Connect subsequent contours of the same shape class
- Brightness alignment of images
- Optional 3d geometry fitting

**Output:**

- Profile shapes
- Wire-frame model
- Textured model
Output of our approach

1. Image preprocessing
   - rotation compensation and cylinder mapping

2. Feature point detection and tracking
   - apply KLT tracker

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4. Global optimization
   - correct camera path and 3D geometry

5. Measuring
   - classify profiles, create 3D model

- camera poses
- 3D point cloud
- profiles
- 3D model
Tests and applications

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Example test sequence for shaft reconstruction

- Diameter: 100 cm
- Diameter: 60 cm
- Depth: 3 m
- Size: 100x100 cm
Evaluation of profile measurements

Average diameter estimation error for 57 sequences

- with correction
- no correction
- (mean + std.dev.)

Success rate of diameter estimation
Variate intrinsic camera parameters (here: max. angle ± 2°)

Systematic reconstruction error (here: up to 15 cm)

Compensation by global geometric correction
Runtime evaluation (offline)

- Original application (offline) \( \Rightarrow \) 2 – 3 frames per second
- Computation on CPU
- RANSAC with many iterations needed for robustness

**Initialization:** \(~800 \text{ ms} / \text{frame}\)

<table>
<thead>
<tr>
<th>Image preprocessing</th>
<th>KLT tracking</th>
<th>Structure from Motion</th>
</tr>
</thead>
</table>

**Tracking:** \(~380 \text{ ms} / \text{frame}\)

<table>
<thead>
<tr>
<th>Image preprocessing</th>
<th>KLT tracking</th>
<th>SfM</th>
<th>Profile measuring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.75 s</td>
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</tbody>
</table>

Global correction
Realtime application (on site) \(\Rightarrow\) \(~7\) frames per second

- Image preprocessing and KLT tracking on GPU
- Use Preemptive RANSAC instead of RANSAC

**Initialization:** \(~240\) ms / frame

<table>
<thead>
<tr>
<th></th>
<th>IP</th>
<th>KLT</th>
<th>SfM</th>
<th></th>
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<tbody>
<tr>
<td>Time</td>
<td>0.25 s</td>
<td>0.5 s</td>
<td>0.75 s</td>
<td>1 s</td>
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**Tracking:** \(~140\) ms / frame

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Time</td>
<td>0.25 s</td>
<td>0.5 s</td>
<td>0.75 s</td>
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<tr>
<td>KLT</td>
<td></td>
<td></td>
<td>Global correction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Profile measuring</td>
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</tbody>
</table>
Use camera poses for manual measuring

- Manual selection of measuring points in camera image
- Automatic correspondence search in subsequent image
- Triangulation of 3d point using known camera poses
- Compute measurements in 3d space (e.g. distance)
Visualization of 3d models

Kiel Elmschenhagen #3
Kiel Hürth #1
Kiel Nordmarksportfeld #1
Conclusion

- Image Acquisition and Structure from Motion
- Our reconstruction approach
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Conclusion

- Robust automatic approach for image-based 3d reconstruction of sewer pipes and shafts with IBAK Panoramo / SI
- Simple geometric correction replaces Bundle Adjustment
- Creation of 3d models for visualization
- Manual measuring in camera images using computed camera poses
- Real-time capability to use on-site
- Successful application to practise
Thank you for your attention!