Real-Time Image-based Topological Localization in Large Outdoor Environments

David M. Bradley, Rashmi Patel, Nicolas Vandapel, Scott M. Thayer
Carnegie Mellon University
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Localization in Large Unstructured Environments

- Large scale environments
- Variable lighting conditions
- Demonstrated real-time localization
- Image-based feature matching
- On-board local sensing with prior map
- Research philosophy:
  - Data association is the weak link
Localization to a prior map

- Camera image varies continuously as camera moves
  → 3D manifold in high-dimensional image space
- Image feature vectors are stored for each location \((x, y, \theta)\)
  → Reduced storage and matching costs
  → Reduce sensitivity to noise
- Close in feature space → close in physical space

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Gradient Orientation Histograms

- Divide image into sub-regions
- Histogram the image gradient orientation weighted by its magnitude
- Concatenate histograms into one vector
- Threshold and normalize
- Inspired by [1] and Similar to feature used in [2]
- Compare descriptors using:

\[ d(X_i, X_j) = 1 - X_i X_j^T \]


Fort Indiantown Gap Test

- 100k pairs of GPS-tagged images
- 70 km accumulated driving
# Fort Indiantown Gap Data Set

## Paths Driven

<table>
<thead>
<tr>
<th>Weather</th>
<th># of runs</th>
<th>Avg. # of images</th>
<th>Avg. path length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunny</td>
<td>10</td>
<td>4723</td>
<td>2.8 km</td>
</tr>
<tr>
<td>Overcast</td>
<td>8</td>
<td>4919</td>
<td>3.05 km</td>
</tr>
<tr>
<td>Dusk</td>
<td>2</td>
<td>4333</td>
<td>2.8 km</td>
</tr>
<tr>
<td>Night</td>
<td>3</td>
<td>4044</td>
<td>3.1 km</td>
</tr>
</tbody>
</table>

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Real-time Localization

- Nearest neighbor found for each new observation
- If feature-space distance < threshold, accept match
- 7 Hz operation with a prior map of 4700 images
  → Limited by feature creation, not comparison
Sample Matching Results

Onboard Camera

On Target Path

Path Deviation Detection Results Video

time: 0.0s
distance traveled: 0.01km
speed: 7.1mph

best match fd: 0.02
certainty: 100%

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Probabilistic Localization Error Bounds

Feature space threshold set to detect 50% of pairs within 3 m and 9°

**Overcast**

P(match error < X) for PD>=0.500

**Sunny**

P(match error < X) for PD>=0.500

Probability that feature-space matches were taken within X m

Random Chance

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Overcast Conditions

- > 90% probability of detection with 6% false alarm rate
- Similar performance across imaging frequency bands and resolutions

Note change in scale
Sunny Conditions

• > 80% probability of detection with 6% false alarm rate
• Strong shadows change as the sun moves
• CCD saturates when sun is in FOV
  → High Dynamic range environment

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Night-time Conditions

- >50% probability of detection with 6% false alarm rate

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Performance Between Environmental Conditions

- Salt and pepper noise
- Strong Shadows
- Drastic lighting change

Night - NIR

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Perceptual Aliasing

- Robot kidnapping problem at every iteration
- Similar areas require filtering over time to reject false positives
Conclusions

• Pruning method
  → Low computational and storage requirements

• Sufficient Accuracy for large environments

• Resolve ambiguities with more expensive:
  → Temporal Filtering
    – HMM [3]
    – Maximum Likelihood [4]
  → Perceptual features
    – SIFT

• Helpful if the environment constrains the robots configuration space

• Currently working on increasing feature robustness across illumination changes

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Why have RGB and NIR?