Camera based soiling monitoring of mirrors

Joe Coventry, Charles-Alexis Asselineau*, Ehab Salahat, and Robert Mahony
APSRC 2019, 3rd of December 2019, Canberra.

* Presenter
Outline

• Motivations

• Fly system and image acquisition

• Image processing

• Conclusions
**Motivations**

The Tracking Cleanliness Sensor (TraCS) + D&S-15R + Side-by-side soiling monitoring kit + Kipp & Zonen DustIQ instrument

**Measurement of soiling - current practice**
• Soiling rates are not consistent:
  – In time
  – In space

• Many other factors impact soiling
  – Cooling tower drift
  – Dust levels
  – Frequency of rainfall
  – Wind direction and speed
  – Overnight condensation
  – Mirror location in the field
  – Whether or not site dirt roads are watered
  – **Ability to enforce vehicle speed limits**

• The value proposition for a robotic inspection system is in three areas:
  – Reduction in the cost of inspection: **automation**
  – Reduction in the cost of cleaning: **time and space resolution**
  – Improvement in performance: **optimisation**
Outline

• Motivations

• Fly system and image acquisition

• Image processing

• Conclusions
Fly system and image acquisition

- Original plan:
  - Fly system:
    - DJI hexacopter
    - 42.2 megapixels with 90 mm lens
    - Laptop with Litchi (DJI controller)
  - Images:
    - Flight 8-9 m above a heliostat field, aiming to maximise field of view
    - 600 m² mirror area imaged
    - High resolution images (~6 pxls/mm²)

Airborne image of a heliostat  Sony a7RII 42.4 MP camera with a 90 mm zoom lens  DJI Matrice 600 hexacopter
Fly system and image acquisition

- **Difficulties:**
  - Working under extreme temperatures (>40°C): random shutdowns, drone height variations.
  - Accuracy of the GPS insufficient
  - Fly time is limited with heavy payload
  - **No commercial solution**

- **Solutions:**
  - Later static tests of an RTK system reduced position error range from 2 m to just a few cm
  - Smaller payload (camera)
  - Open source system

![Results from the RTK experiments](image)

_Aeronavics Skyjib Coax Octocopter_
Fly system and image acquisition

- **Waypoint planning:**
  - Taking images of every single heliostat is impractical
  - Sampling a set of mirrors allows results to be interpreted within some known confidence level with a given error margin
  - Waypoint planning is used to generate a real-time path to the target heliostats

\[ w_k = [x_k, y_k, z_k, \phi^1_k, \phi^2_k, \phi^3_k] \]

where \( x_k, y_k, \) and \( z_k \) are the longitude, latitude and altitude \( \phi^1_k, \phi^2_k, \) and \( \phi^3_k \) are roll, pitch, and yaw angles of the camera orientation.

<table>
<thead>
<tr>
<th>Sample size</th>
<th>( \mathcal{K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence level</td>
<td>( \mathcal{C} \in [0,1] )</td>
</tr>
<tr>
<td>Heliostat population</td>
<td>( \mathcal{N} )</td>
</tr>
<tr>
<td>Error margin</td>
<td>( \mathcal{\varepsilon} )</td>
</tr>
<tr>
<td>Inverse complementary function</td>
<td>( \mathcal{Q} )</td>
</tr>
<tr>
<td>Proportionality constant</td>
<td>( \mathcal{p} \in [0,1] )</td>
</tr>
</tbody>
</table>

\[ z = \sqrt{2\mathcal{Q}(1 - \mathcal{C})} \]

\[ \mathcal{K} = \left[ \frac{\xi}{1 + \xi/\mathcal{N}} \right] \]

where \( \xi = \frac{z^2p(1-p)}{\mathcal{\varepsilon}^2} \)

- e.g. heliostat field with \( \mathcal{N} = 10,000 \) heliostats can be sampled with a confidence level \( \mathcal{C} = 0.95 \) and an error of \( \mathcal{\varepsilon} = 0.05 \) with a random inspection of \( \mathcal{K} = 370 \) heliostats only

(a) Full-search and (b) travelling salesman waypoints planning for an example heliostat field.
Outline

• Motivations

• Fly system and image acquisition

• Image processing

• Conclusions
1. Image segmentation

2. Identification
   • GPS precision
   • Good survey data!

3. Raw processing:
4. Soiling detection: Finding the sky

- Key problems:
  - It is not possible to resolve dirt using high resolution cameras
- Intensity variations:
• **Classification:**
  - Soiling is brighter than the sky and corrosion darker.
  - Robust filtering to get the sky surface model
  - Filtering with a pre-defined distance $\rho_s$ above, or $\rho_c$ below the surface model
  - Green and blue channels are used

• **Estimation:**
  - All colour channels are used together
  - Fit a gaussian mixture model to the 3D colour space data using ML techniques (EM algorithm).
  - Pixel sky/soiling is given as probability of single modes.
• Validation experiment:
  • A 800 mm x 800 mm region of a representative mirror was sub-divided into 6 x 6 grid

• 9 reflection measurements per cell taken with a D&S 15R-US portable reflectometer.

• Average value treated as the ground truth reflectance for that cell.

<table>
<thead>
<tr>
<th>Corrosion Level</th>
<th>Soiling Level</th>
<th>Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Soiling, Low Corrosion</td>
<td>1, 7, 13, 19, 25, 31</td>
<td></td>
</tr>
<tr>
<td>Low Soiling, Moderate Corrosion</td>
<td>2, 8, 14, 20, 26, 32</td>
<td></td>
</tr>
<tr>
<td>Low Soiling, High Corrosion</td>
<td>3, 9, 15, 21, 27, 33</td>
<td></td>
</tr>
<tr>
<td>Moderate Soiling, Low Corrosion</td>
<td>4, 10, 16, 22, 28, 34</td>
<td></td>
</tr>
<tr>
<td>Moderate Soiling, Moderate Corrosion</td>
<td>5, 11, 17, 23, 29, 35</td>
<td></td>
</tr>
<tr>
<td>Moderate Soiling, Moderate Corrosion</td>
<td>6, 12, 18, 24, 30, 36</td>
<td></td>
</tr>
</tbody>
</table>
• Deviation from ground truth using classification:

Relative reflectivity error w.r.t. the ground truth value for (a) cells with less than 5% error and (b) more than 5%.

Note the different y-axis scales

• 29 out of the 36 cells have error in the reflectance estimate relative to the ground truth less than 5%, with all such cells corresponding to cases 1, 3 and 5.
• With average soiling levels rarely exceeding ~5% in a commercial heliostat field, for reflectance data to be useful it is likely to need accuracy <1%.
  • Classification works but has limits (resolution, color confusion)

• First results on estimation:
  • Measured average mirror reflectance was 86.8 %
  • Method gives 84.3% = 88.5% x 95.2% (clean mirror reflectance)
  • WORK IN PROGRESS
Outline

• Motivations

• Fly system and image acquisition

• Image processing

• Conclusions
Conclusions

- The method has successfully demonstrated that mirror inspection from a drone using high resolution images can yield data about soiling and other mirror defects.
- Improvements to the image processing are underway.
- Project finishes this year... There is a lot more to do!

Acknowledgement
This project is supported by the Australian Renewable Energy Agency (ARENA).

Contact: joe.coventry@anu.edu.au