Sensing and control of segmented mirrors with a Pyramid wavefront sensor

Context of study: HARMONI & ELT

HARMONI

• SCAO system analysis
  ➢ 100x100 PYR WFS @ 500 Hz, in I-Band
• Nominal seeing
  ➢ 0.65” (r0≈15cm), 30° zenith, high flux

Segmented deformable mirror (M4)

• Segmented thin shell made of 6 discontinuous petals
• Petals have a common reference body

Secondary mirror unit: Spiders

• Supported by six 50 cm wide spiders > r0
• Matching the 6-petal geometry
• One PYR pixel is 37cm (D/100) < 50cm
Motivation: Impact of large spiders & M4

No spiders & continuous DM
- Good performance (pure AO perf.)
  - 101 nm RMS residual error
- Good stability
  - ± 4 nm

Spiders & M4
- Very poor performance
  - > 5000 nm RMS res. error
  - Additional differential piston between petals > ±7 waves
Differential piston: Atmosphere + Islands

- Differential piston is present in atmospheric turbulence

  ![Turbulent phase cut](image1)

  ![Phase difference at spider edges](image2)

- For large gaps, differential piston not well sensed by the WFS
  - PYR or SH
  - \(\pi\) ambiguity (\(\lambda\) jumps)

- Additional unwanted term is injected by AO loop

  ![Atmospheric created diff. piston](image3)

  ![Diff. piston introduced by AO loop](image4)
**Handling differential pistons**

- **Provide a simple solution to**
  - Remove diff. pistons in the presence of turbulence ($\Delta \phi_{AO}$)
  - Correct atmospheric differential pistons ($\Delta \phi_{ATM}$)

- $\Delta \phi_{AO}$ & $\Delta \phi_{ATM}$ are of the same order of magnitude
  - Hard to disentangle

- **SCAO error budget study**
  - 70nm RMS of additional diff. piston is acceptable to meet specifications (in quadrature)
Handling differential pistons: WFS

- **Existing solution: add another WFS**
  - Differential piston can be sensed modulo $\lambda$
  - $WFS_1$ at $\lambda$ & $WFS_2$ at $\lambda + \Delta \lambda$
  - Increased cost and complexity!

- **Crazy ideas (for HARMONI)**
  - WFSing at longer $\lambda$ to have spider width $\leq r_0$.
    - Detector in K-Band? + Using science photons!
  - Add information under the footprints of the spiders
    - Fourier extrapolation
    - Defocusing the WFS
    - Phase on either side of spiders is decorrelated: Cannot create correct information

Handling differential pistons: WFS

• Valid detector pixels & modulation
  - Useful signal is contained in the diffracted light
    - Include region under the spiders’ shadow
  - Diffracted light outside the pupil footprint comes with small modulation
    - Keep modulation as small as possible
    - Choice: 3 or 5λ/D
  - Gaps=0.5m & pixels=0.37m (D/100)
    - Little signal is present!
  - It’s a prerequisite but it’s insufficient

Pinna et al, "Why not use the pyramid to phase your ELT?", Wavefront Sensing in the VLT/ELT era, Marseille (2016)
Removing diff. piston from commands

- Filtering out segment pistons in correction phase
  - Atmosphere contains segment pistons ($\Delta \phi_{\text{ATM}}$)
  - Leads to truncated correction phase & ultimately poor performance

- Penalty on the commands
  - $c = (M^TM+\alpha V^TV)^{-1}M^Ts$. $V$ contains the mode to be rejected such that $v_i^Tc<\varepsilon$
  - The $\alpha$ parameter allows for selectivity and trade-off
  - We can penalise 1st derivatives, curvature, step at the DM edges etc.
  - Difficult trade-off that might change from frame to frame

- Relying on prior information
  - Use pseudo-open loop control
  - Rely on phase spatial statistics to smooth the DM commands
  - Initial results are not conclusive. Work in progress!
Phase closure: Estimating the diff. piston

Method

Assume piston can be extracted from edges
1. Average phase along radius at edge of segment
2. Extrapolation of turbulence in the middle of spider based on each segment phase (linear, spline…)
3. Solve linear system (6 unknowns, 6 measurements) to find piston of each segment

2nd step: Extrapolate piston

Constant [1 pt]

Linear regression

Spline regression
Phase closure: Results

- **Clear gain observed**
  - Average residual error: 165 nm RMS
  - Large variation: max 371 nm

- **Data averaging methods**
  - Radial averaging along edges
  - Actuator position or phase
  - With and without time averaging ($\Delta \phi_{ATM}$ has slow dynamics)

- **Basic limitations of the method**
  - Loss of continuity b/c gaps larger than correlation distance
  - Biased estimation of information used to ensure continuity

- **Conclusion**
  - Phase extrapolation + phase closure doesn’t perform well enough
  - Island error: 134 nm! $>>$ 70nm
Slaving actuators: Approach

- **Goal**
  - Impose continuity of the DM surface

- **Approach details**
  - Pair-wise coupling of edge actuators
  - Common reference body gives absolute position of the 6 DM petals

- **Drawbacks**
  - We loose in actuators count (162 DoF)
  - Completely negligible in error budget
    - Fitting error from 85nm to 86nm
Slaving actuators: Results

- **Good average performance**
  - 107 nm RMS (in median seeing conditions 0.65")

- **Good stability**
  - Min 100 nm & max 140 nm

- **Remaining residual errors**
  - The unwanted differential piston is strongly reduced but a small amount remains
  - Possible improvements
    - Currently using scalar gain: may be improved by modal gain
    - Or by combining w/ other methods
Results summary

Pure AO performance

<table>
<thead>
<tr>
<th></th>
<th>Average residual error</th>
<th>Additional error term</th>
<th>Strehl in K</th>
</tr>
</thead>
<tbody>
<tr>
<td>No spiders</td>
<td>101 nm RMS</td>
<td>-</td>
<td>92%</td>
</tr>
<tr>
<td>No correction</td>
<td>&gt; 5000 nm RMS</td>
<td>+ 5000 nm</td>
<td>0%</td>
</tr>
<tr>
<td>Regularisation</td>
<td>Work in progress</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Closure</td>
<td>168 nm RMS</td>
<td>+ 134 nm</td>
<td>86%</td>
</tr>
<tr>
<td>Slaving</td>
<td>107 nm RMS</td>
<td>+ 35 nm</td>
<td>91%</td>
</tr>
</tbody>
</table>

70nm RMS additional differential piston is acceptable to meet specifications

Long exposure (5sec) PSF comparison (K-Band)

- No spiders
- No Correction
- Closure
- Slaving

Wavefront Sensing
Control
Deformable Mirror
Conclusions

• Investigated both WFS and control based solutions
  - None of the WFS-only solutions are conclusive on their own.
  - We tried several methods ensuring the continuity of the phase across the pupil → Doesn’t deliver the required correction levels.
  - Regularisation is still work in progress

• We propose a simple and robust solution
  - It relies on position/voltage control (i.e. slaving the edge actuators) combined with a small PYR modulation
  - It relies on knowing the absolute position of the 6 DM petals (ref. body)
  - Works for SCAO, to be demonstrated for LTAO

• Remaining work
  - Improvements
    ▪ Combine with optimal modal gain for an optimal control of the filtered modes
    ▪ Ensure solution compatible with a force actuators
  - Further analysis
    ▪ How does the correction performs as a function of seeing?
    ▪ Performance as a function of SNR (NGS magnitude)