Correlation algorithms for the new generation of solar telescopes

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MCAO Test-bench

- Objective: gain experience and knowledge with different AO solutions to provide an optimal MCAO solution for the EST.
- General requirements: different AO configurations (SCAO, GLAO, MCAO), number of DMS and different types of SH-WFS.
- Control requirements:
  - Several control schemes (leaky-integrator, POLC,..)
  - Several correlation techniques
  - Should be able to work with zonal and modal control
  - Loop conditions similar to those for EST ➔ dynamic conditions scaled and comparable
- Equipment:
  - Ground layer DM: ALPAO 820-acts
  - Altitude DMs: ALPAO 2x 468-acts
  - 2xSH-WFS
    - High order (on-axis and binning): 3002x3952 px
    - High-order Multi-directional: 6004x7920 px
  - Server: 4x Xeon Gold, 384 Gb RAM
- RTC Software: Durham Adaptive Optics Real Time controller (DARC), used in GTCAO
MCAO Test-bench
MCAO Test-bench

Focus translation table

Pinhole array

820-acts DM

Sun slide

X translation table

High order On-axis WFS

Multi-directional WFS

Pinhole array
Let’s see the numbers!

• Dynamic scaling: cameras only go up to 30 fps!
• Turbulence generator: phase screens that dynamically create an atmosphere equivalent to EST’s, scaled to 30 Hz.
• Objective: build a control loop able to work at 30 Hz.
• Working with the High-order on-axis (10 “):
  • 3002x3952 px
  • ~849 subaps \( \Rightarrow \) 1698 slopes measurements
  • 40x40 px per subap (0.25”/px)
  • This is the case for SCAO \( \Rightarrow \) good performance obtained (González-Cava et al., 2022), using standard differences squared + quadratic fit.
• And for the multidirectional?
  • Directions are picked by software
  • 7 directions (33 “ circumference, 10 “ per subwindow) \( \Rightarrow \) ~5943 subwindows = 11886 slopes
  • 19 directions (60 “ circumference, 10 “ per subwindow) \( \Rightarrow \) ~16131 subwindows = 32262 slopes
  • 25x25px per subwindow (0.3”/px) \( \Rightarrow \) more subaps, smaller patterns to match
So... what’s the problem?

Situation: GLAO, using the multidirectional WFS:

- Squared differences + parabolic $\Rightarrow$ works fine, but speed is a problem
- Using 7 directions, subapertures of 25x25px $\Rightarrow$ ~18 Hz (30 Hz expected)

➢ Easiest solution: clip the window
Situation: GLAO, using the multidirectional WFS:

- Squared differences + parabolic ➔
- Using 7 directions, subapertures of 25x25px, clipping 6 px per size ➔ 13x13 px to compute the correlation (25.6 Hz now!)

➢ However,.. What about robustness and accuracy?
• We applied a 6 px displacement over the Y-axis using our translation table
• Some slopes measurements are lost

Typical solutions:
• Discard the slopes out of the subapertures
• Change the subpixel algorithm, maybe CoG, to force the slope to be inside of the subapertures

However, our purpose is to learn more about the behaviour of the algorithms
Correlation surface

- Correlation images shown as surfaces, vertex of the quadratic fit in red

This is not a good solution, we need to find the performance using other correlation methods
Evaluation of image-shift measurement algorithms for solar Shack-Hartmann wavefront sensor, M.G Löfdahl (2010)

- Use of artificial data to evaluate the impact of the correlation algorithms in the accuracy on the shifts estimation

Relevant conclusions for our analysis:

1. Squared differences with quadratic fit offers less systematic errors
2. Fourier based correlation tends to underestimate small shifts ( < 3 px)
3. For closed loop applications, Fourier correlations might be as good as Squared differences

Let’s take a look at Fourier-based correlation
Performance & 3D

Same conditions: 25x25 px subaperture, 7 directions
Rate: 28.4 Hz (without clipping)

Surface for a displacement of 6 px, same as previous situation

Important difference: low contrast in the correlation image
Subpixel algorithms might be influenced by this low contrasting!

Maybe this is the cause of FFT underperforming squared differences?
Experimental results at the test bench

- Squared differences: overestimates large shift
- FFT: underestimates small shift
- Both behaviors are coherent with Löfdahl (2010)
- Small shifts are important for closed-loop!
Contrast improvement

Steps
- Length normalization
- Correlation background removal → take N highest valued pixels of the correlation image

Finally, CoG will be effective for the resulting image (without background)

- Result similar to Squared Differences, very accurate with the real displacement
- Spikes can be found in certain subapertures, should not be relevant for control performance
- Number of pixels should be picked carefully
Correlating large images requires a deeper analysis on correlation algorithms behavior.

We have tested the two classical algorithms for correlating solar images: squared differences and FFT, as well as the two main subpixel algorithms CoG and Quadratic fit.

The experimental behavior of both algorithms is coherent with simulation results of previous studies.

By understanding the contrasting problems of FFT we have developed a simple method, easy and robust to implement in any system, achieving the same performance as squared differences, the best classical method (widely used).
Thanks!