Numerically Closing the Loop of the Adaptive Optics Sensor: the Validation of the Comsol Simulation

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Compensating the Atmospheric Turbulence
The Control System Concept

AdOpt IF
Del Vecchio et al.

Rationale
Background
Introduction
Images vs Simulations
Numerical Approach
Interferometric Data
Data Matching
Results
Summary
A *feed-forward*, open-loop correction dramatically increases the closed-loop response of the servo system. This correction is based on the DM stiffness matrix ... ... operatively defined by arbitrarily displacing one actuator, while all the others are constrained at 0, and calculating the reaction forces. The *influence function* (IF) is the shape of the DM when poking a single actuator.
The Control System
Improving the Closed-Loop Response

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- This correction is based on the DM stiffness matrix . . .
- . . . operatively defined by arbitrarily displacing one actuator, while all the others are constrained at 0, and calculating the reaction forces.
- The *influence function* (IF) is the shape of the DM when poking a single actuator.
The Case Study
The VLT Zerodur DM

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### The VLT Zerodur DM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>( R_o )</td>
<td>558 mm</td>
</tr>
<tr>
<td>( R_i )</td>
<td>48 mm</td>
</tr>
<tr>
<td>( t_m )</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>( R_b )</td>
<td>4575.30 mm</td>
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<tr>
<td>( K_b )</td>
<td>0</td>
</tr>
<tr>
<td>( R_f )</td>
<td>4575.3 mm</td>
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<tr>
<td>( K_f )</td>
<td>-1.66926</td>
</tr>
<tr>
<td>( N )</td>
<td>1170</td>
</tr>
</tbody>
</table>

Convex Very Large Telescope DM [Biasi et al., 2012]
The Previous Results
A Necessary condition

OPTICAL DATA $\leftrightarrow$ MATCHING $\Rightarrow$ FEA

Already demonstrated for LBT and VLT mirror local stiffness

[Del Vecchio et al., 2013]

- Expanding the method to the whole DM allows
  - get rid of obscurations
  - avoid complex data processing @ edges
  - easier calibration

provided that the FEA matches the experimental data
Images vs Simulations

- optical calibration $\leftrightarrow$ 1170 Influence Functions
  - IF$_i$ = image of $w_k = \begin{cases} 0 & \text{if } k \neq i \\ w^* & \text{if } k = i \end{cases}$

- the actuator is moved until the set point via the capsens reading (close loop)
- the capsens signal is converted from an average capacitance signal, lower than the actual magnet position
- the real IF deformation field differs from the actuation command in the FEM
- a suitable operator makes the transformation
The Simulation I
The actual capsens implies too large models

Can we *squeeze* an annulus into a circumference?
The Simulation II
Approximating the capsens signal

\[ C = \int_0^{2\pi} \int_{r_i}^{r_o} \frac{\varepsilon}{z(r, \theta)} r dr d\theta = \frac{\varepsilon A}{z^*} \]

\[ \frac{1}{z^*} = \frac{1}{A} \int_0^{2\pi} \int_{r_i}^{r_o} \frac{1}{z(r, \theta)} r dr d\theta \]

Taylor expansion of \( \frac{1}{z} \) around \( r^* \) \( \forall \theta \)

\[ r^* = \frac{2}{3} \frac{r_o^2 + r_i^2 + r_o r_i}{r_o + r_i} \] minimizes the error
The Simulation III
Modelling tricks

- insert 1170 circumferences of radius $r^*$
- mesh them with only 22 triangles (*Delaunay method*)
Verifying the $r^*$ approximation on two VLT actuators

# 8 @ (0.063,0) (edge)  
error < 3.5%

# 312 @ (0.291,0) (central)  
error < 1%
Simulation Results II
The VLT *capsens* displacements

Typical std/rms ratio ≈ 1%
**Processing the Interferometric Data I**

**Interferometric Data**

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**Experimental IFs**

Interferometric data sets $\leftrightarrow$ mirror deformation map

**How the IF Data Are Collected**

- displacement $+c$ applied to the $i$th actuator (an image $w_i^1$ is captured)
- displacement $-c$ applied to the $i$th actuator (an image $w_i^2$ is captured)
- repeating these steps $N$ times, $2N$ frames are obtained

resulting image: $w_m = \frac{1}{N} \sum_{i=1}^{N} \frac{(w_i^1 - w_i^2)}{2c}$
Processing the Interferometric Data II

Interferometric Data

FRAME RATE = 25 Hz

EACH $w_m$ FRAME IS CORRECTED FOR TIP-TILT AND

DEFOCUS

PISTON ADJUSTED SO THAT $|w_m| = 0$ AFTER MASKING THE

IF PEAK

$w_m$ IS FINALLY NORMALIZED TO UNITARY MAXIMUM VALUE

Image noise = 0.014

Given by the convection residuals, it’s computed as the

RMS of the images after masking out the actuated region

to be compared with the unitary IF peak value
Data Matching I

\[ \mathbf{F}_m \xrightarrow{\mathbf{M}} \mathbf{F}_c \]

- \( \mathbf{F}_m \) = model IF data (actuator displaced at the magnet locations)
- \( \mathbf{F}_c \) = image (actuator displaced at the capacitive sensor ones)
- \( \mathbf{M} = n_{act} \times n_{act} \) transformation matrix: \( \mathbf{M}(i,j) = \) value of \( \mathbf{F}_m(i,j) \) (ith IF, jth actuator) averaged over the capacitive sensor ring as mapped on \( \mathbf{F}_m \)
- \( \mathbf{F}_c = \mathbf{M}^{-1} \mathbf{F}_m \)
- Each \( \mathbf{F}_c \) image is finally re-aligned to match the interferometer images geometry normalized to unitary maximum value

As a result, \( \mathbf{F}_c \) and interferometer images are directly comparable*

* The uncertainties in the identification of the capsens areas and in the images alignment are possibly responsible for systematic errors in the analysis of the subtraction residuals
Data Matching II
Comparison

- take a 80 by 80 pixels area centered at the actuator locations (a grid of $5 \times 5$ actuators — the IF is practically flat outside this area); (figure will follow)

- $F_c$ images $\ominus$ experimental data = difference map

- compute the RMS of the difference for each IF; (figure will follow)
Results I
The Overall Response
Results I
The Overall Response

- **849 of 1170 actuators (colored dots)**
  - \(0.011 \leq \text{RMS difference} \leq 0.043\)
  - applied displacement = 1
  - \(\approx 60\% \text{ of values is } \leq 0.02\)
  - typical experimental data noise = 0.014
- maximum values close to the edges

- **321 of 1170 actuators (black dots)**
  - inner and outer DM edges
  - areas obscured by the spiders
  - some bad pixels
The VLT displacement around actuator #312

The difference spans from $-0.089$ to $0.057$

Although it shows some residue structures, noticeable at the actuator locations, the global matching is within the experimental noise.
Lessons Learned & Future Work

**The matching strategy**

**COMSOL IFs and interferometric measures**

Numerical data vs measured data

Difference \( \approx \) experimental noise

**Suitable Comsol tools replicate the measures**

A completely numeric, highly accurate control system is achievable

**Future developments**

Funding request submitted last Monday
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