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Design and modeling of the off-axis parabolic deformable (OPD) mirror laboratory

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Coronagraph Optical Train (LUVOIR)

- Need 2 deformable mirrors (DMs) for wavefront sensing and control
- Long separation between DMs for amplitude and phase mixing
- High actuator count DMs

Issues:
Packaging issues
Higher risk of actuator failure
Low Actuator Count Parabolic DMs

Groff et al. 2016
Comparing Broadband Performance

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Center Contrast</th>
<th>10% Average</th>
<th>20% Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM at Plane C</td>
<td>$4.974 \times 10^{-7}$</td>
<td>$5.033 \times 10^{-7}$</td>
<td>$5.178 \times 10^{-7}$</td>
</tr>
<tr>
<td>DMs at A1,A2,B1,B2, Aberr. at C</td>
<td>$1.374 \times 10^{-7}$</td>
<td>$1.609 \times 10^{-7}$</td>
<td>$2.636 \times 10^{-7}$</td>
</tr>
<tr>
<td>DMs at A1,A2,B1,B2, No Aberr. at C</td>
<td>$8.30 \times 10^{-8}$</td>
<td>$9.92 \times 10^{-8}$</td>
<td>$1.634 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Groff et al. 2016
Advantages of Parabolic DMs

• Simplifies the packaging issue for space missions

• Reduces both cost and risk of having the entire coronagraph instrument’s performance depending on one or two high-actuator count DMs

• Increase in achievable bandwidth correction
  - Controllable surfaces are in conjugate planes to the sources of aberrations.
Lab layout NASA Goddard
Instrument Details

- Coronagraph
- PSF
- Focal Plane/ Zernike Mask
Instrument Details

• Flat Pupil DM
  - BMC 32 x 32 DM
• Parabolic DM
  - Modified ALPAO 11 x11 DM
DM simulations

• Actuator resolution
  - Round up to nearest 10 pm or 100 pm

• Stability
  - Percent stability of the voltage/amplitude applied
    - 0.5%, 1%, and 2%

• Bandwidth 20%

• Assumptions:
  - Perfect Estimation
  - No amplitude aberrations
Error Maps Used for Simulation

a) Pupil Error Map (nm)

b) Parabolic DM Surface Errors (nm)

b) Flat DM Surface Errors (nm)
Selected Design Requirements and Result

- Stability of 0.5% and actuator resolution of 0.1 nm
Other Experiments

- The lab is multipurpose and following experiments to be carried out
  - Non-linear dark hole digging
  - Adaptive estimation of line-of-sight jitter (LOS)
  - Machine learning for LOWFS
Linear vs Non-linear Control

Linear Estimation and Control

\[ z = Hx + n \]
\[ \hat{x} = (H^T H)^{-1} H^T z \]

\[ W_k = (G_k u_k - \delta E_k)^T (G_k u_k - \delta E_k) + \alpha_k^2 u_k^T u_k \]
\[ u_{w,k} = (G_k^T G_k + \alpha_k^2 I)^{-1} G_k^T \delta E_k. \]

Figure from Groff et al. 2016

Non-linear control

\[
\text{minimize } W = \sum_{DH} I, \text{ where } I = f(A_{\text{im}}, \Phi_{\text{im}}, V_{\text{DM}}) \\
= |A_{\text{im}} e^{\Phi_{\text{im}}}|^2 \\
W = \sum_{DH} |A_{\text{im}} e^{\Phi_{\text{im}}}|^2 \\
= \sum_{DH} A_{\text{im}}^2
\]

Estimation: \( A_{\text{abb}}, \Phi_{\text{abb}} \)
Control: Just need a single DM?!
Non-linear Control

• DM voltage calculated by non-linear optimization
  - Python L-BFGS-B (quasi-Newton method)
  - Minimize cost function, provide the gradient

• Cost Function
  - Obtained by forward model of the system

• Gradient
  - Obtained by algorithmic differentiation* of each step of the forward model

* Jurling et al.
Simulation Results

• Three different coronagraphs
• Different combination of phase and amplitude error

1) Ripple 3 SPC

2) Lab coronagraph with segments errors

3) LUVOIR B Coronagraph
Adaptive Estimation of LOS

In Simulation, we have shown that residual after correction 0.4 mas.

Assumptions:
- Reaction wheel speed changing over time
- 2.4 telescope observing a star of magnitude 4.83
LOWFS - Machine Learning
Conclusion

• Making OAPs deformable is advantageous
  • Improvement control bandwidth
  • Better for packaging
  • Less risk and cost

• At NASA GSFC we are designing a multipurpose testbed
  • To test parabolic DM architecture
  • Different control algorithms
    - Non-linear dark hole digging, line-of-sight and LOWFS estimation and control