Fourier-Based Predictive AO Schemes for Tomographic AO systems

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Outline

1. The mechanics of Fourier predictive control
2. Implementing multi-layer predictive control
3. Extending Fourier predictive control to tomographic systems: Simulations
4. Application to GEMS telemetry
We will Implement Predictive Control on the Upgraded Shane AO System

◆ Project funded by the University of California Office of the President

◆ Goals:

◆ Develop LQG tomographic predictive control for MCAO and MOAO systems

◆ Implement single-conjugate predictive control on the upgraded Shane LGS AO system at Lick Observatory
Closed-Loop Kalman Filters Require a State Space Model of the Turbulence

Optimal control schemes use a model:

• We need a model of both the control system and the operating conditions (e.g. noise level and atmosphere)

• For best performance, we need to be “data-driven” and use actual WFS telemetry to populate our model

  • Getting wind velocity a little wrong is OK
  • Getting wind direction a lot wrong is very bad
• Predictive control uses the state space model to “evolve” the measurements a few milliseconds into the future, eliminating time delay error

• Most successful in high-wind or low S/N (low frame rate) environments, when time delay error becomes important
ShaneAO: Adaptive Optics System at the Shane 3-meter Telescope (LGS mode, new fiber laser)

- ShaneAO is a diffraction-limited imager, spectrograph, and polarimeter for the visible and near-infrared science bands.
Shane AO will deliver improved Strehl over existing Lick system.

Strehl vs Wavelength

LGS mode, new fiber laser

Airy core forming

Wavelength, nm

Strehl

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# ShaneAO Instrument Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector sampling</td>
<td>0.035 arcsec/pixel</td>
</tr>
<tr>
<td>Field of view</td>
<td>20 arcsec square</td>
</tr>
<tr>
<td>Science detector: Hawaii2RG</td>
<td>Hawaii2RG</td>
</tr>
<tr>
<td>Science wavelength coverage: 0.7 to 2.2 microns</td>
<td>0.7 to 2.2 microns</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>R = 500</td>
</tr>
<tr>
<td>Slit width: 0.1 arcseconds</td>
<td>0.1 arcsec</td>
</tr>
<tr>
<td>Slit decker: 10 arcseconds (?)</td>
<td>10 arcsec</td>
</tr>
<tr>
<td>Slit angle on sky</td>
<td>adjustable 0-360°</td>
</tr>
<tr>
<td>Long-exposure stability</td>
<td>hold to the diffraction-limit for one hour</td>
</tr>
<tr>
<td></td>
<td>hold to ½ slit width for 4 hours</td>
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<tr>
<td>Polarimetry mode:</td>
<td>polarization analyzer and variable angle waveplate</td>
</tr>
<tr>
<td>Delta magnitude within seeing disk</td>
<td>Dm_K = 10</td>
</tr>
<tr>
<td>Minimum brightness tip/tilt star:</td>
<td>m_V = 18</td>
</tr>
<tr>
<td>Tip/tilt star selection field</td>
<td>120 arcsec</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>~90% LGS mode</td>
</tr>
<tr>
<td>Minimum brightness natural guide star</td>
<td>m_V = 13</td>
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<tr>
<td>Camera readout modes</td>
<td>Correlated double-sampling (CDS)</td>
</tr>
<tr>
<td></td>
<td>up the ramp (UTR)</td>
</tr>
<tr>
<td></td>
<td>sub-frame region of interest (ROI)</td>
</tr>
<tr>
<td></td>
<td>quick take</td>
</tr>
<tr>
<td>Exposure support:</td>
<td>Multiple frame co-added</td>
</tr>
<tr>
<td></td>
<td>automated nod and expose coordinated with telescope (snap-i-diff, box-4, box-5)</td>
</tr>
<tr>
<td></td>
<td>automated darks sequence based of history of science exposures</td>
</tr>
<tr>
<td>Observations support</td>
<td>automatic data logging</td>
</tr>
<tr>
<td></td>
<td>automatic data archiving</td>
</tr>
</tbody>
</table>

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ShaneAO is being Assembled with First Light in Fall 2013

Deformable Mirror

Wavefront Sensor

Science Detector

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Use General Kalman Solution for Arbitrary Time Delays

\[
C(z) = \left( \frac{Q^{-1} \sum_{k=0}^{L} \frac{p_{L+1,k}}{1 - \alpha_k z^{-1} \left[-\Delta + (1 + \Delta) \alpha_k\right]} \left[1 + z^{-1} Q^{-1} \sum_{k=0}^{L} p_{L+1,k} \left[(1 - \Delta) + \Delta \alpha_k\right]\right]}{1 + z^{-1} Q^{-1} \sum_{k=0}^{L} p_{L+1,k} \left[(1 - \Delta) + \Delta \alpha_k\right]} \right)^{-1}.
\]

(34)

1 fr < Delay < 2 fr

Delay < 1 frame

\[
C(z) = \left( \frac{Q^{-1} \sum_{k=0}^{L} \frac{p_{L+1,k} \alpha_k}{1 - \alpha_k z^{-1} \left[(1 - \Delta) + \Delta \alpha_k\right]} \left[1 - \alpha_k z^{-1} \left(1 - \Delta + \Delta z^{-1}\right) \left(1 - \Delta + \Delta \alpha_k\right)\right]}{1 - \alpha_k z^{-1} \left(1 - \Delta + \Delta z^{-1}\right) \left(1 - \Delta + \Delta \alpha_k\right)} \right)^{-1}.
\]

(37)

Poyneer et al. 2008
Application to GEMS Telemetry

- Method #1: Apply wind identification step to pseudo open-loop slopes provided by A. Guesalaga and B. Neichel

- Method #2:
  1. Perform tomographic reconstruction on pseudo open-loop slopes to estimate true volumetric phase
  2. Apply wind identification step to layers of different atmospheric heights

*We expect that wind layers separated by height will have different temporal properties.*
Tomographic Reconstruction + Wind Identification Cleanly Separates Layers

The temporal properties of layers are cleanly distinguished by a tomographic reconstruction (using only geometric information!).

Pseudo Open-Loop slopes

Tomographically-reconstructed ground layer

Tomographically-reconstructed 4.5 km layer
Solution for Closed-Loop MCAO with Tomography

- Residual WFS Slopes
  - Fourier Reconstructor
  - Residual WFS Phase
    - Tomographic Estimator
  - Residual Layer Phase
    - Layer 1 integrator
    - Layer 2 integrator
    - Layer 3 integrator
    - Layer 1 Kalman
    - Layer 2 Kalman
    - Layer 3 Kalman
  - SOL phase
  - Found peaks
  - Solve Riccati Eqs
  - DMs Layer Phase
  - DM Projections
Advantages over Filtering WFS Slopes

◆ Wind Identification performed on pseudo open-loop phase at each layer, not wavefront sensor phase

◆ Approach makes physical sense – uncorrelated layers are likely to be at different altitudes

◆ Apply a prior that wind vectors in layers separated by geometric tomography should be uncorrelated.

◆ If a wind peak is seen with a certain vector that corresponds to a stronger detection in another layer, reject those frequencies.
We simulate an 10-m MCAO system with tomography:

- 3-10 LGSs over 100” diameter
- 8-layer Mauna Kea atmospheric model
- Reconstruction over 3 layers (0, 5, 10 km)
- Wind velocities randomized, 0-15 m/s
- 200 realizations of 4 second length, 1 kHz operation
- 3 DMs at reconstructed altitudes (30x30 up to 45x45)
Minimum Variance Back-Projection Tomography (Gavel 2004)

\[
\begin{align*}
\mathbf{v}_{k+1} &= \mathbf{v}_k + \Delta \mathbf{v}_k \\
\Delta \mathbf{v}_k &= a \mathbf{C} \mathbf{e}_k \\
\mathbf{e}_k &= \mathbf{y} - (\mathbf{A} \mathbf{P} \mathbf{A}^T + \mathbf{N}) \mathbf{v}_k \\
x &= \mathbf{P} \mathbf{A}^T \mathbf{v}_\infty \\
x &= \mathbf{P} \mathbf{A}^T (\mathbf{A} \mathbf{P} \mathbf{A} + \mathbf{N})^{-1} \mathbf{y}
\end{align*}
\]

- 5 iterations per time step, alternating pre-conditioned conjugate gradient / linear steps, warm restart
Tomographic Error Mixes Temporal Signals between Altitudes

Layer 1: 0 km

Layer 2: 5 km

Layer 3: 10 km

10 m/s

DC

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Results: Kalman Filtering Reduces Delay Error by 3x

- 500 Hz frame rate, 2 step delay, $r_{0,500} = 15$ cm
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- 500 Hz frame rate, 2 step delay, $r_{0,500} = 15$ cm
Correction Scheme – Shift & Average Multi-sampled Voxels

\[ \Phi'(r, t') = \frac{1}{n' - n_0 + 1} \sum_{n=n_0}^{n'} \Phi(r - c(n' - n)v, cn) \]

- Wind Identification and Estimation not simulated
- For each layer, replace voxels in downwind direction with shifted and averaged voxels from tomographic time history
- Only shift voxels originating in multi-sampled region, where height can be effectively determined
- Wind vectors assumed to be known perfectly

Phase height cannot be constrained in sparsely-sampled regions from tomography alone!
Prediction Improves RMS Errors on Layer Estimates

- After 1 second, on average, the layer estimates improve 3-13%
- Downwind regions improve 10-30%, especially for high altitude layers
Prediction Improves RMS Errors on Layer Estimates

- With downwind layers better determined, the tomographic error improves beyond the radius of the guide stars

Maps of Improvement in Layer Estimates

Tomographic Error vs. Field Radius

Without shift & average

With shift & average

LGS radius

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Goal: Test Fourier-Based Predictive Tomography on UCSC Testbed

- Up to 8 wavefront guide stars and 4 tip/tilt stars
- 10,000 DOF per DM (100x100 subaperture Hartmann sensors)
- Up to 3 DMs (MCAO) or 1 DM and open loop WFS path (MOAO)
- 5 Hz sample & control rate
- Moving phase plates (wind)
- Moving LGS fibers in z to simulate LGS elongation, or laser pulse
1. Fourier Predictive Control is a computationally efficient method of reducing delay errors

2. In simulation, shifting and averaging predictive control provides 3-13% benefits in tomographic wavefront estimation quality at all layers

3. From GEMS telemetry: Adding a tomographic reconstruction to pseudo-open loop slopes, using geometric information only, cleanly separates the temporal properties of the wind flow.

4. In an MCAO simulation, predictive control reduces time lag errors by 3x for a realistic implementation (500 Hz, 2 step delay)