LASER METROLOGY SENSING AND CONTROL FOR LARGE SEGMENTED-MIRROR TELESCOPES

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Outline

• Introduction
• Optical hexapod
• Swept-frequency laser metrology
  - Absolute optical pathlength measurement
  - Relative optical pathlength measurement
• Discussion
Background

- Wavefront sensing and control for large segmented telescopes always a challenge (both technically and financially)
- Edge sensors have been successfully used in some large segmented systems such as Keck, HET, SALT, etc.
  - Draw back of edge sensors include:
    - M1 – M2 distance not measured
    - M1 global curvature not measured
    - Limited control bandwidth due to computational complexity
- This paper describes a laser metrology system that could be used for segmented mirror telescope control
Use of laser metrology truss to tie all the segments together with a common reference such as M2
Optical hexapod 6DOF (tripod 3DOF) for segmented telescopes
Optical Hexapod (OHP) Concept

- Six (6) laser beams between two rigid panels (M1 and M2)
- Three reference points on each rigid panel
- All 6 DOF between two panels are measured
Optical Hexapod (OHP) Concept

Common fiducials (3) on M2

M1 panels with embedded beam launchers

Holey corner-cubes on M1 panels

Holey corner-cubes on M1 panels
Swept-frequency laser metrology

REF beam launcher with a calibrated REF cavity

Metrology source

Fiber distribution

Beam Launcher

Φ_R

Beam Launcher

Φ_M

A

B

X_M

X_R
Swept Frequency Absolute Ranging

- Phase from a COPHI beam launcher
  \[ \phi = \phi_1 - \phi_2 = \frac{4\pi}{\lambda} x = \frac{4\pi}{c} f_o x \]
- Swept the laser frequency \((\Delta f_o)\)
- Measure phase changes in both MEAS and REF beam launchers
  \[
  \begin{align*}
  \Delta \phi_M &= \frac{4\pi}{c} x_M \Delta f_o \\
  \Delta \phi_R &= \frac{4\pi}{c} x_R \Delta f_o
  \end{align*}
  \]
- Calculate MEAS distance:
  \[ x_M = x_R \frac{\Delta \phi_M}{\Delta \phi_R} \]
- Least-square fit to achieve high accuracy
Phase Measurement – Abs and Rel Modes

Absolute Mode

Relative Mode

REF and UNK phases during ABS mode (x1)

Displacement measured for calibration

Phase changes (Fringes)

Displacement (nm)

Time (sec)

Time (sec)
REF Cavity Calibration – Method #1

• Use white-light Michelson interferometer:
  - REF cavity in one arm
  - Mirror on translation stage in the other arm
  - Measure displacement of the mirror between two white-light fringes
    • Optical encoder ~1um
    • DMI ~3nm

• REF cavity thermal stability: ~0.01ppm/C° (ULE material)
Absolute pathlength ~ 1-3 um over 1m distance

REF cavity length calibration requires improvement and independent verification
Can laser metrology be useful in ground-based telescopes?

- Laser metrology and edge sensors to actively align and control the telescope:
  - Primary mirror surface figure
  - Distance between primary and secondary mirrors
Measurement in the lab with open air

- 80 ft long open optical path
- Optical table with folded mirrors
- Ambient temperature (21°C +/- 1°C)
- Relative humidity (43%).
- CTE of optical table ~10^{-5} \Rightarrow 270\mu m/°C
- Index of air (i.e. optical path length) also depends on environment:

\[ n = 1 + 7.86 \cdot 10^{-4} p / (273 + t) - 1.5 \cdot 10^{-11} RH (t^2 + 160) \]

- Turbulence is an important factor for dynamic sensing and control
- Needs more study
Summary

- Described an optical hexapod metrology concept
  - Can work together with edge sensors
  - Can measure M1 – M2 distance and M1 global curvature
- Swept-frequency laser metrology system
  - Absolute optical path length measurement (~1um)
  - Relative optical path length measurement (~nm)
- Air turbulence is a concern for ground-based telescopes and needs further study
Backup slides
Common Path Heterodyne Interferometer (COPHI)

- Measurement and reference signals from spatially separated different parts of the same wavefront
  - Reduced optical cross-talk
  - Improve thermal stability (common path)
  - Variety of configurations for different types of measurements

\[ V_{REF} = \sin(2\pi f_o t_o) \]

\[ V_{MEAS} = \sin \left( 2\pi f_o t + \frac{2\pi}{\lambda} x \right) \]

\[ \phi_{MEAS} - \phi_{REF} = \frac{2\pi}{\lambda} x \]
Scaling Laws

- Mechanical optical error scales to the 4th power of aperture diameter (Peterson, et al.)

\[ \delta \propto \frac{D^4}{h^2 E} \frac{1}{\rho} f(v)g(P) \]

- The larger the aperture, the more (a lot more!) challenge on structures

- Metrology sensor error scales linearly with the dimension

\[ \delta x_M = \frac{\delta x_R}{\Delta \phi_R} \Delta \phi_M = \frac{\delta x_R}{x_R} x_M \]

- Save your $$ and kg from structures to build metrology?

Build a very rigid back structure and a simple metrology system or a low-cost back structure and a very capable metrology system to correct for deformations? Where is the optimum?