CubeSat Deformable Mirror Demonstration (CDMD)

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Is there other life out there?
edearthobservatory.nasa.gov
Reflected starlight: spectra

- Look at absorption features in spectra: O2, H2O
But stars are really bright...

http://photojournal.jpl.nasa.gov/catalog/PIA04204
• Must block starlight to see planets around star
Use a coronagraph to block the star’s light
Basic Coronagraph Optics

• If life were perfect…

1. Input Pupil
2. Image Plane
3. Reimaged Pupil
4. Reimaged... Image Plane

\[ \theta \]

Pupil stop
Star blocker
Lyot stop
Detector

Fourier Transform
Inverse Fourier Transform
Fourier Transform

Figure adapted from Traub & Oppenheimer 2010
The star 55 Cancri observed with the Lyot Project coronagraph at AEOS in Maui. The symmetric "speckles" arising from atmospheric effects and imperfections in the telescope optics are clear. http://www.lyot.org/results
Corrupting an innocent wavefront

- Cosine ripple $\rightarrow$ symmetric speckles

1. Input Pupil
2. Image Plane
   - Fourier Transform
3. Reimaged Pupil
   - Inverse Fourier Transform
4. Reimaged...
   - Image Plane
   - Fourier Transform

- Pupil stop
- Star blocker
- Lyot stop
- Detector
• 2D FFT of X, Y ripple pattern (e.g. surface error, stray light)
• Lower spatial frequencies at center, higher outside
  – Outside is where planets will be, need dark hole → Deformable Mirror
• N actuators per side of a DM, null N/2 waves, \( \theta (\text{dark hole}) = \pm N\lambda / 2D \)

Need deformable mirror with lots of actuators... in space.
The first time to try this is not on a $1B space telescope.
Single deformable mirror example

Light source
Single mode fiber-coupled laser 650 nm

Log10 Contrast Ratio Planet/Star

R. Belikov (NASA Ames), results with polarizer, 6/9/09 (in 2011, 5.4 x 10^-8)
MEMS Deformable Mirrors

- Actuators change the shape of the mirror surface to match the incoming wavefront

- MEMS devices
  - Electrostatic actuators
  - Stroke of $\approx 1-8 \, \mu m$
  - Higher voltage, low current
  - More actuators
  - Fast response time

Stewart et al. 2007
Wavefront Control System

- Plane Wave
- Distorted Wavefront
- Actuator Drive Signals
- Drivers
- Deformable Mirror
- Corrected Wavefront
- Wavefront Sensor
- Data Processor
- Corrected Image

Images:
- Initial PSF
- PSF with turbulence (D/r0 = 2)
- Corrected PSF
• Measure wavefront and calculate phase error to be corrected

• Sensored
  – Optical element introduced into beam to generate measurement

• Sensorless
  – Intensity-based measurements, computationally intensive
Lab prototype

CubeSat-scale setup

Z(2,-2), 2xy

Shack Hartmann Spots

MATLAB simulation and controller
• On-orbit performance of MEMS DM
• DMs will fit
  – Same actuator technology as big ones
    • BMC Mini MEMS DM, 32 actuators
    • Iris AO PTT111, 37 segment
    • Drive electronics board will also fit
• Laser Diode
  – “Easy” ADCS
  – Aperture can look at stars when laser off
    • But don’t really care which star(s)
    • Need only to have slew rate ~ 5 arcmin/s
Leveraging experience with MicroMAS, simpler ADCS
CDMD

Payload Overview

- Boston Micromachines Mini MEMS DM
  - 32 actuators, 5 cm diameter, 2.21 cm tall
  - ~150 g including cables
  - Driver board
    - Existing board nearly CubeSat form factor
    - Straightforward to respin

- Optics
  - DM has >= 1.5 mm aperture
  - UV-grade fused silica
    - Lenses, beamsplitter, ND filters, lenslet array, quarter wave plate
    - Stress-free mounts, lens tubes

- Detector
  - IDS UI-5241LE-M, CMOS (or similar)
  - Closed loop wavefront control; processor
Shack-Hartmann Wavefront Sensing System

1. Aperture Lens
2. Collimating Lens
3. Polarizing Lens
4. Polarizing Lens
5. Flat Mirror
6. Beamsplitters
7. Quarter Waveplate
Shack-Hartmann Wavefront Sensing System

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Shack-Hartmann Lenslet Array

- Incoming beam dictated by DM aperture
- Maximize sub-lenses / mm^2
- If lens is 10 mm x 10 mm, with 150 μm pitch = ~67 x 67 spots. So, for an incoming beam diameter of 2.25, about 15 x 15 spots.
- Need at least 4 pixels per spot, so for detector, need the 2.25mm beam to cover more than 60 x 60 pixels.
Beam Divergence

Assumptions:
1. Beam is circular
2. No additional beam divergence through optical components

\[ \theta = 2 \arctan \left( \frac{D_f - D_i}{2L} \right) \]
• Avionics Requirements
  – Camera interface / readout
  – Low frame rate image processing
    • Centroid, delta x and delta y, slope reconstruction
    • Linear algebra for mirror controller

• Possible solutions
  – PC104 form factor single board computer
  – Raspberry Pi
    • Also low-speed camera option
    • 5 MO OmniVision 5467 (60 fps at 720p)
  – ODroid-X2
    • ARM, standard peripherals
• Laboratory development
  – Optical tolerancing, payload trades (Zemax)
  – Wavefront sensing, quantify DM reconstruction capability
    • Accuracy as function of # lenslets, alignment, tolerancing
    • Optimize wavefront reconstruction data products
      – Centroids, delta x, delta y, Zernike or Fourier coefficients
  – Update mirror drive electronics
  – Avionics design and testing

• Environmental tests on mirrors, drivers (ref. Shea et al. 2006)
  – Mechanical, electrical, follow up with ground efforts

• Partners, sponsors, launch opportunities, logistics
Design and build cost-effective, small wavefront control CubeSat to characterize high actuator-count MEMS deformable mirrors.

Enable implementation of active/adaptive optics with MEMS DMs on future space missions.

High contrast imaging.
Precision pointing.
Modulation.
Thank you!

Give’on, Amir, Belikov, Ruslan, Shaklan, Stuart, Kasdin, Jeremy. “Closed-loop, DM diversity-based, wavefront correction algorithm for high contrast imaging systems”


[14] University at Buffalo, ‘GLADOS’, University Nanosat Program 7 Flight Competition Review


Backup Slides
Michelson Interferometer with Flat Mirror on NanoPositioner

- Laser
- Flat Mirror on NanoPositioner
- Deformable Mirrors
- Detector

Dimensions:
- 95 mm
- 145 mm
## Payload Requirements

<table>
<thead>
<tr>
<th>ID</th>
<th>Statement</th>
<th>Relevant parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLD-1</td>
<td>The payload shall command a MEMS deformable mirror to run a pre-defined test sequence for at least 5 minutes [TBR] each orbit.</td>
<td>All</td>
</tr>
<tr>
<td>PLD-1.1</td>
<td>The payload shall have the ability to control any combination of actuators within 0.001 [TBR] seconds of each other, at a minimum rate of 100 Hz [TBR], with a minimum stroke of 1.5 microns, and with a precision of at least 1 nm [TBR].</td>
<td>Deformable Mirror</td>
</tr>
<tr>
<td>PLD-2</td>
<td>The payload shall have the ability to measure and reconstruct the optical wavefront at one wavelength for the duration of a 5 minute [TBR] test sequence each orbit.</td>
<td>Avionics Interface</td>
</tr>
<tr>
<td>PLD-2.1</td>
<td>The payload shall have the ability to measure the optical wavefront at a minimum rate of 100 Hz [TBR]</td>
<td>Detector, Avionics</td>
</tr>
<tr>
<td>PLD-2.2</td>
<td>The payload shall have the ability to reconstruct the optical wavefront with a minimum accuracy of 100 nm rms [TBR].</td>
<td>SH array, Detector</td>
</tr>
</tbody>
</table>
Example: Find beam diameter

Beam leaves laser with divergence Θ, and effective diameter $D_i$, and travels to polarizer, a distance $L$ away. What is the beam diameter $D_f$ entering the polarizer?

For the CPS186 laser:
- $\Theta \leq 1.8 \text{ mrad}$
- $D_i = 1.2309 \text{ mm}$

\[
\Theta = 2 \arctan \left( \frac{D_f - D_i}{2L} \right)
\]

\[
(1.8 \text{ mrad}) = 2 \arctan \left( \frac{D_f - 1.2309 \text{ mm}}{2(11 \text{ mm})} \right)
\]

\[
D_f = 2(11 \text{ mm}) \times \tan \left( \frac{1.8 \text{ mrad}}{2} \right) + 1.2309 \text{ mm} = 1.2507 \text{ mm}
\]

At the detector: $D_f \approx 1.5859 \text{ mm}$
Absorption, Reflectivity, and Polarization

Assumptions:
1. Beam is circular
2. No power/intensity lost between components (small distances)

\[ P = \int I \cdot dA \]
Example: Find beam intensity

Beam leaves laser with power $P$, and effective diameter $D_i$, and travels to polarizer. What is the beam intensity after going through the polarizer?

For the CPS186 laser:
- $P = 4.70 \text{ mW}$
- $D_i = 1.2309 \text{ mm}$

\[
P_i = \int I_i \cdot dA
\]
\[
P_i \approx I_i \left( \pi r_i^2 \right)
\]
\[
\therefore I_i \approx \frac{P_i}{\pi \left( \frac{D_i}{2} \right)^2} = \frac{4.7 \text{ mW}}{\pi \left( \frac{1.2309 \text{ mm}}{2} \right)^2} = 3.9497 \text{ mW/mm}^2
\]

At the detector:
- $I_f \approx 1.2411 \text{ mW/mm}^2$
- $P \approx 2.4514 \text{ mW}$
Actuator:

3- orthogonal torque coils
- Light weight, low power actuator
- Provide actuation for active magnetic control

Sensors

• Magnetometer
  - Provide reading of local magnetic field for magnetic control
  - Provide attitude knowledge in eclipse

• Sun Sensors
  - Provide attitude knowledge in daytime

• IMU
  - Provide angular rate knowledge for vibration damping
Torque Coil Design

<table>
<thead>
<tr>
<th>Total Mass</th>
<th>520 g</th>
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<tbody>
<tr>
<td>Max Total Power</td>
<td>1.35 W</td>
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<table>
<thead>
<tr>
<th>Direction</th>
<th>Z</th>
<th>X, Y</th>
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<tbody>
<tr>
<td>Size</td>
<td>10 cm × 10 cm</td>
<td>10 cm x 30 cm</td>
</tr>
<tr>
<td>Quantity</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Turns</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Current</td>
<td>0.12 A</td>
<td>0.04 A</td>
</tr>
<tr>
<td>Wire Gauge</td>
<td>28 AWG</td>
<td>28 AWG</td>
</tr>
<tr>
<td>Magnetic moment</td>
<td>0.60 A*m^2</td>
<td>0.60 A*m^2</td>
</tr>
</tbody>
</table>

T. Nguyen