Abstract—The high contrast requirement of $10^{10}$ needed to directly image an Earth-like exoplanet around a sun-like star at optical wavelengths requires space telescopes equipped with coronagraphs and wavefront control systems. Coronagraphs are needed to block the parent star's light and improve the ability of the system to detect photons that have reflected off of the exoplanet toward the observer. Wavefront control systems are needed to correct image plane aberrations and speckles caused by imperfections, thermal distortions, and diffraction in the telescope and optics that would otherwise corrupt the wavefront and ruin the desired contrast. The two key elements of wavefront control systems are (1) a way to detect the wavefront distortions (a wavefront sensor) and (2) a way to correct the distortions before the image plane (such as deformable mirrors, or DMs). In this paper, we investigate a compact and inexpensive CubeSat-based wavefront control testbed that can be used as a technology development precursor toward a larger mission.

Index Terms—Adaptive optics, extrasolar planet, microelectromechanical systems, space technology

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I. INTRODUCTION

Adaptive optics systems that utilize deformable mirrors were introduced by the defense community in 1981 and expanded to the science community after declassification in 1991 [1]. While applications such as high-contrast imaging with space telescopes [2] [3] and space-based free-space optical laser communications [4] [5] do exist, implementation and functional performance assessments of a deformable mirror wavefront control system have not yet been demonstrated in orbit, at least, not on a civilian mission. The proposed CubeSat Deformable Mirror Demonstration (DeMi) will take a first step toward incorporation of small, low-power, high actuator count deformable mirror wavefront control systems on spacecraft for use in high-performance space telescope and free-space laser communication systems.

Applications of wavefront control systems in space can be grouped into four general categories: (1) systems that take images through the Earth’s turbulent atmosphere, (2) systems that transmit and receive laser signals through the Earth’s atmosphere, (3) systems that take high-contrast and high-dynamic-range images of other objects in space, and (4) systems that transmit laser signals to and receive laser signals from other objects in space. In addition to wavefront control and correction, deformable mirrors can also be used as the amplitude or phase modulators that code transmitted signals in free-space laser communication systems.

Adaptive optics systems that compensate for atmospheric turbulence are typically designed to perform with faster speeds and larger strokes than wavefront control systems that do not compensate for atmospheric turbulence. A two-mirror woofer/tweeter (coarse—fine) wavefront control approach is frequently used [6], where the woofer corrects slower, larger amplitude, lower-frequency components and the tweeter corrects faster, smaller amplitude, higher-frequency components. The DeMi mission focuses on developing a low-cost, easy-access-to-space platform for validating technologies used for the tweeters: the more complex, higher actuator count DMs.
Typically the pointing errors, static errors, and noise are the primary sources of wavefront errors that need to be managed. Speckles that result from diffraction at the edge of the pupil can be reduced to an acceptable level (for example, thermal drifts), but scientific observation should be limited to a certain area of the sky. In cooperation with the spacecraft attitude control, wavefront control techniques can be used to reduce the phase errors to an acceptable level even for large ground-based telescopes with high-performance adaptive optics systems and an ideal coronagraph.

For a space telescope to make high-contrast observations, it needs to be able to use gas absorption features from molecules in the atmosphere of an Earth-like exoplanet. A space telescope will require wavefront control, even though the space telescope is far above the Earth’s atmosphere. It has been demonstrated in space that a high-performance wavefront coronagraph is capable of directly imaging Earth-like exoplanets. The goal is to have an area of high contrast around the star that is large enough to extend into the "habitable zone" where an Earth-like planet might exist.

A. Reducing risk for future missions

The development of a space telescope equipped with a high-performance coronagraph and wavefront control system that is capable of the $10^{10}$ contrast needed to directly image Earth-like exoplanets is expected to be on the order of several hundreds of millions of dollars to over a billion dollars. It is important to demonstrate the technology to be used on these proposed missions to reduce both technical and programmatic risk.

Lower mass, power, and size are the primary advantages of using MEMS deformable mirrors for space applications. The Boston Micromachines Mini MEMS DM referenced in this work is representative of its larger, higher-actuator-count siblings; the difference is the chip size. It uses electrostatic parallel-plate actuators that are coupled to a continuous facesheet mirror through mechanical attachment posts. However, wavefront control with MEMS DMs has not yet been demonstrated in space. In addition to the Boston Micromachines MEMS DM discussed for our initial testbed concept, there are other MEMS DMs (e.g., IrisAO) as well as other small form factor deformable mirror technologies (e.g., Xenetics) and ASIC driver technologies (e.g., Microscale) that could be integrated and evaluated on future CubeSat platforms based on DeMi.

While several important environmental tests can be performed using these mirrors on the ground (thermal vacuum,
vibration, life cycle testing, radiation), it is important to demonstrate that simple wavefront control systems utilizing these new deformable mirror technologies have stable, well-calibrated, and predictable on-orbit performance. There is no opportunity to manually “tweak” or “adjust” a wavefront control system after launch. It is of particular importance to fully develop robust flight software to calibrate and control these mirrors and systems, to incorporate them as sensors with spacecraft attitude determination and control systems (ADCS), estimators, and fine pointing algorithms, and to determine how best to capture performance and calibration data along with science observations and transmit to ground.

B. CubeSat Background

The CubeSat form factor was developed by California Polytechnic Institute (CalPoly) and Stanford University in 1999. It interfaces with a common secondary payload deployer, the Poly-picosatellite Orbital Deployer (P-POD), which significantly reduces the cost and time for obtaining launch opportunities for nanosatellites. The basic nanosatellite unit is a 10 x 10 x 10 cm cube (called 1U). The P-POD unit will support a 3U volume in a variety of combinations [17]. CubeSats are usually launched as secondary payloads on government or commercial primary missions, with their launch accommodation often sponsored by government agencies, such as the NASA Educational Launch of Nanosatellites (ELaNa) program. A 3U CubeSat is an appropriate platform for the DeMi mission and wavefront control demonstration because it enables a comparatively quick, simple, low-cost approach for a technology demonstration that would have significant impacts on the design, scale, and capabilities of future space-based optical systems.

C. Paper Organization

Section II describes concept of operations and overview of wavefront control demonstration. In Section III we discuss supporting subsystems and trades. Section IV contains details on the supporting CubeSat subsystems. Section V concludes with a summary and plans for future work.

II. PAYLOAD DESCRIPTION

For this demonstration mission, the design is kept simple, with a goal of using as much existing commercial off the shelf (COTS) hardware as possible. Other than the deformable mirror and detector, there are a few fixed optical elements including a flat mirror, a beamsplitter, a couple of collimating and focusing lenses, and a neutral density filter for the internal diode laser source. Follow-on missions can build in complexity off of this baseline. The first priority is to demonstrate that the deformable mirror can be commanded and controlled on-orbit, to characterize its performance, and to show that its on-orbit behavior is understandable and predictable. This goal can be accomplished using only an internal coherent light source such as a laser diode to illuminate the mirror and a detector to image it. While an internal light source is the simplest approach, it would be more interesting and useful to design a system that could also image a bright external source, such as a star like Arcturus or Vega, or even a bright satellite such as the ISS. As a first step in characterizing the utility of a MEMS DM, the DeMi mission does not have a requirement on wavefront control performance.

Figure 1 contains a basic overview diagram of an optical layout that supports imaging of an external target as well as an internal light source. The system captures three images: (1) the target without influence from the DM, (2) the target as seen by the DM, and (3) the target as seen by a standard Shack Hartmann wavefront sensor after the DM. This allows wavefront estimation and interpretation both by using just the DM (such as phase diversity) as well as using the SH wavefront sensor to demonstrate onboard closed-loop wavefront control. The beam containing the “point” source object (e.g., ISS which is bright, or other bright stars such as Arcturus or Vega) is resized and collimated by lenses L1 (the aperture) and L2 (collimating lens) and divided by a beam splitter (B1) oriented 45 degrees to the beam. Following along the first branch, the reflected beam travels to an image-focusing lens after which it is focused and imaged on the CCD (Image 1). On the second branch after beam splitter B1, the transmitted beam reaches the deformable mirror. From the DM, the beam travels to another beamsplitter (B2) that splits the beam between a Shack-Hartmann lenslet array that acts as a wavefront sensor imaging subapertures onto the detector (Image 2), and a flat mirror that travels to another focusing lens to place the corrected image on the detector (Image 3).

| TABLE 1 | BOSTON MICROMACHINES MINI MEMS DM OPTIONS [15] |
|---|---|---|---|
| Stroke | 1.5 µm | 3.5 µm | 5.5 µm |
| Aperture | 1.5 mm | 2.0 mm | 2.25 mm |
| Pitch | 300 µm | 400 µm | 450 µm |
| Approx. Mechanical Response Time (10%—90%) | 20 µs | 100 µs | 500 µs |
| Approx. Interactuator Coupling (+/-5%) | 15% | 13% | 22% |

The three resulting images are read out and processed by electronics onboard the spacecraft. The uncorrected Image 1 will be compared with the image from the beamsplitter (Image 3) to verify system functionality. The image created from the Shack-Hartmann lenslet array (Image 2) will be used to sense and reconstruct the wavefront, and in closed-loop mode, it will provide feedback to alter the configuration of the deformable mirror to achieve the desired correction.

A calibrating low-power diode laser is also included as an internal source and would follow a similar path to the collimated light from the external point source. In the absence of an external source to the system, the diode laser has the potential to verify operation of the MEMS DM. A heating resistor placed near the aperture of the external lens would be
used to intentionally introduce thermal aberrations to the lenses and motivate the use of the MEMS DM to perform a controlled demonstration on the functionality of the wavefront control system.

A. Payload design trades

To determine the exact configuration and most effective spacing of the optical elements within the payload, further modeling and component-level trade studies are required. Assembly of a test-bench system in a laboratory setting will provide insight into the feasibility of the proposed design. To date, a CubeSat-sized test bench coarse MEMS DM sensing system using an internal laser diode source and simple Michelson interferometer as the “wavefront” detector has been demonstrated.

One of the key trades is the selection of a MEMS DM and the corresponding mirror aperture. Even though the deformable mirrors themselves are quite small, even within their packaging, a widely acknowledged challenge to incorporating high actuator count deformable mirror systems on a spacecraft is the substantial size, mass, volume, power, and complexity of the mirror driver boards and wire harnesses. While development of application-specific integrated circuit (ASIC) drivers is a current focus of several deformable mirror manufacturers [18] [19], it is uncertain when the ASIC drivers will become generally available and whether they will be usable for space applications. In the meantime, a candidate DM has been identified for which both the DM and existing drive electronics should fit, with very little modification, in the ~1.3U CubeSat payload volume remaining of a 3U CubeSat after supporting subsystems are accounted for.

The current DeMi payload design accommodates a “Mini” deformable mirror from the Boston Micromachines Corporation (BMC), and initial studies indicate that it could also accommodate a 37-actuator IrisAO device. The BMC Mini is a 6 x 6 deformable mirror (32-actuators, as the four corners are not active). There are three different stroke and aperture options with the Mini20, as summarized in Table 1 [15].

The Mini DM has 14 bit step resolution and a sub-nm average step size. The fill factor is >99%, the surface finish is < 20 nm RMS, and the driver is completely powered and controlled by a USB 2.0 interface. The frame rate is 8 kHz, with 34 kHz burst. For the DeMi mission, the most recently available BMC Mini packaging format is selected (5 cm diameter and 2.21 cm tall, 75 g without cables). The existing driver board has dimensions of 13 x 10 x 1.8 cm, and there is bare, unused printed circuit board (no traces) for ~2.75 mm on each side of the width dimension, such that the board could have dimensions 13 x 9.5 x 1.8 cm. The initial plan is to use this board with conformal coating, and the connectors would be staked and secured.

A trade study is underway to determine which of the BMC DM options would be best. For example, as shown in Figure 2, with standard Thorlabs lenses, a ½” (12.7 mm) f=50 mm aperture lens (L1) is on the far left. With a 6 mm plano convex f=10 mm L2, this would yield a beam size of ~2.54 mm, which would be close to the 5.5 µm stroke, 2.25 mm aperture DM and could be followed by a 6 mm f=10 mm plano convex imaging lens. For Image (2), instead of an imaging lens, a lenslet array with 150 µm pitch and f=5.2 mm could be used, and would result in ~10 lenslets per side of the beam (100 lenslets total, for a 32-actuator DM).

Figure 2: Concept of the optical element layout drawn to scale to fit as the payload in a 3U CubeSat. With standard Thorlabs lenses, a ½” (12.7 mm) f=50 mm aperture lens (L1) is on the far left. With a 6 mm plano convex f=10 mm L2, this would yield a beam size of ~2.54 mm, which would be close to the 5.5 µm stroke, 2.25 mm aperture DM and could be followed by a 6 mm f=10 mm plano convex imaging lens. For Image (2), instead of an imaging lens, a lenslet array with 150 µm pitch and f=5.2 mm could be used, and would result in ~10 lenslets per side of the beam (100 lenslets total). This aperture would have a ~14.5° FOV. The collimated laser diode is the CPS405 from Thorlabs, a 4.5 mW, 405 nm laser which takes 5 VDC regulated power and has a large survivable temperature range. The beamsplitters (CM1-B5010) are also from Thorlabs, cube-mounted, non-polarizing beamsplitters weighing about 27 g (0.06 lbs.) each.

The collimated laser source is the CPS405 from Thorlabs, a 4.5 mW, 405 nm diode laser which takes 5 VDC regulated power and has a large survivable temperature range. The beamsplitters (CM1-B5010) are also from Thorlabs, cube-mounted, non-polarizing beamsplitters weighing about 27 g (0.06 lbs.) each.
There are different types of detectors that would be appropriate for use, and further study will help us to determine the best pixel size for the optical layout given better estimates of the expected object intensities. If we use a detector with approximately 1.75 μm pixels in the above configuration, there will be ~1,000 pixels per side of the image. We also need to further study whether to pursue a standard COTS detector or use a CCD with space flight heritage. Depending on the size of the selected CCD, the three images will either be collected on separate sections of a single CCD, or split onto two separate CCDs. The image that passes through the Shack–Hartmann lenslet array will be reconstructed on-board as part of the closed-loop wavefront control logic. There are other static wavefront sensors that could be implemented other than the Shack–Hartmann sensor such as a shear prism or interferometer. Since wavefront sensors that use an actuated element, such as a pyramid or curvature wavefront sensor, carry additional risk and complexity in the actuated element, we have not considered them for this initial demonstration.

III. CONCEPT OF OPERATIONS

As a university nanosatellite project, it is desirable to maintain low complexity in design and operations. In addition to stars like Arcturus (HIP 69673) and Vega (HIP 91262), DeMi will image one of the brightest objects in the sky: the International Space Station (ISS). Since a large fraction of United States CubeSat launches are ISS resupply launches, DeMi will be able to image the ISS (mostly as a point source) both early in the mission without atmospheric interference and later in the mission with atmospheric interference as DeMi drifts away from the ISS, as shown in Figure 3 and Figure 4.

Figure 3 shows a simulation of a close separation between DeMi and the ISS (top, ~112 km) and a simulation of a far separation between DeMi and the ISS (bottom, ~4500 km). Figure 4 shows that DeMi cycles periodically through these close-far approach windows every few days during its operational lifetime, and each window has a duration of about 10 hours.

CubeSats that are launched on an ISS resupply mission are typically dropped off in the orbital plane of the ISS at 300 km. The ISS is at roughly 330 km. With dimensions for the ISS of 70 m × 108 m, the angular size of the ISS at a 115 km separation would be ~0.035° and ~0.054°. At 4500 km separation, the angular size would be ~0.0009° and 0.0014°, respectively. Even with the trades available in the optical layout, the ISS would effectively be a point source.

To image the ISS will require a launch on an ISS resupply mission. While imaging the ISS is not a requirement, it does have the added benefit of being a bright target through the atmosphere. ISS resupply missions represent a large fraction of the United States launch opportunities.

A. Mission Phases

The concept of operations involves ground support, launch, deployment, and detumbling, thirty days of commissioning, and ten months of nominal operations and data downlink. During initial detumbling, we anticipate taking images of ISS if the batteries are charged sufficiently to do so without risking the mission. As shown in Figure 4, there should be multiple opportunities for ISS imaging through the nominal mission.

Phase 1 of nominal operations involves calibration with open-loop wavefront sensing of a repeating sequence of mirror surface shapes. During Phase 1 we will also simulate the effects of bad actuators on the DM. Phase 2 involves closed-loop wavefront sensing, where feedback from the Shack-Hartmann is sent to the microcontroller on the payload and is used to achieve and maintain a desired surface shape on the DM. This is followed by Phase 3, during which the CubeSat images the ISS or other bright stars. The goal is to image the ISS at both closest approach and near the horizon to investigate adaptive optics through the atmosphere in space.
As part of all mission phases, the additional resistive heating element will be activated to induce distortions in the image; in the second and third phases, the deformable mirror will attempt to correct these distortions.

DeMi can explore the limits of a compact, space-based active wavefront control system with varying amounts of atmospheric interference. By testing adaptive optics imaging of larger satellites, DeMi paves the way for more sensitive compact space-based adaptive optics systems, which could image much smaller objects through varying amounts of atmospheric interference.

IV. SUBSYSTEMS

Since a CubeSat has all of the functionality of a larger satellite, it also requires fully functional, although miniaturized, versions of major satellite subsystems. Designs for the necessary subsystems to support the DeMi mission are presented for the attitude control and determination (ADCS), Power, Communications and Avionics, Thermal, and Structures subsystems.

A. Power

Two solar panel configurations were modeled in STK: (i) a set of four, 3U body-mounted panels, and (ii) a set of four two-sided 3U deployed solar panels and no body-mounted panels. Each 3U surface holds 7 ultra-triple junction solar cells. In each case, the spacecraft is oriented with the long axis parallel to the zenith-nadir line. The results from power generation calculations for a series of orbital altitudes and inclinations for each configuration for one orbit are shown in Figure 5 and summarized in Table 2.

In Figure 5, our initial models show that the while peak power generation is generally higher with the deployed panels, the body-mounted panels provide more uniform power generation pattern across the orbit. Table 2 compares the orbit averaged power (averaged over daylight, non-zero power generation) numerically for each case.

<table>
<thead>
<tr>
<th>Orbital Inclination (degrees)</th>
<th>Orbital Altitude (km)</th>
<th>4 x 3U Body-Mounted Panels Orbit Avg. Generated Power (W)</th>
<th>4 x two-sided 3U Deployed Panels Orbit Avg. Generated Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300</td>
<td>12.3</td>
<td>12.0</td>
</tr>
<tr>
<td>0</td>
<td>400</td>
<td>12.4</td>
<td>11.9</td>
</tr>
<tr>
<td>45</td>
<td>300</td>
<td>11.9</td>
<td>12.1</td>
</tr>
<tr>
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</tr>
<tr>
<td>90</td>
<td>500</td>
<td>15.0</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 5: Top: power generated by 3U body-mounted solar panels over the course of an orbit. Bottom: power generated by four two-sided 3U deployable solar panels over the course of an orbit.

While the peak power generation is higher from the deployed solar panel configuration, a calculation of the orbit-averaged power shows that the body-mounted panel generation is more favorable than that of the deployed panels for the case where the body-mounted solar panels will not be obstructed or missing, for example, due to the P-POD deployment interface and the desire for cabling for ground testing. Using solely deployed panels does not provide a significant increase in power generation, it makes for a less consistent power profile, and deployed panels add unnecessary complexity and cost to the spacecraft. For these reasons, the current design utilizes four 3U body-mounted panels.

If further analysis shows that more power generation is required, there are a few options that can be considered. One is to utilize deployed panels in conjunction with body-mounted panels. Another is to design the spacecraft to enable sun pointing, which would require a more robust ADCS design.

B. Structure

The basic structure of the spacecraft is a 3U CubeSat with body-mounted solar panels. Figure 6 shows two views of the spacecraft: one showing the 3U skeleton with volume-representative parts, and one showing the outer solar panel structure.

A preliminary placement of the subsystem boards and payloads within the 3U CubeSat volume is shown in Figure 7. The microcontroller and motherboards are from Pumpkin Inc., the batteries and electrical power system (EPS) are from Clyde Space, and the structure is a modified Pumpkin 3U skeletonized chassis. The communications board could either be UHF or S-band and would be supplied by one of several suppliers such as L-3 Communications, Clyde Space, AstroDev, or Espace, Inc. The payload takes up a volume of approximately 1.4U.
D. Thermal

The baseline thermal design is a passive system with the exception of the Clyde Space battery, which includes internal heaters, and the payload heater to introduce aberrations in the lens. A comprehensive thermal model of the satellite and a more in-depth analysis of the payload components will determine the need for active thermal management. Small flexible heater circuits may be required for spot thermal management.

E. Communications and Avionics

The communications system will include a UHF transceiver. There are several commercial options for CubeSat UHF transceivers as well as ground stations and support from the amateur radio community. The DeMi mission currently has baselined a UHF L-3 Communications Cadet Nanosatellite Radio. The primary ground station would be the 18 meter dish at NASA Wallops, with SRI International’s 18 meter dish at Stanford as an alternate. Another communications option is to use an S-band Espace Payload Telemetry System (PTS) operating in the 2.0 to 2.3 GHz range with the recently refurbished Open System of Agile Ground Stations (OSAGS) facilities at Kwajalein, Cayenne, and Singapore. The OSAGS system has a control center on MIT campus as it was previously used to support the NASA High Energy Transient Explorer (HETE-2) mission.

V. SUMMARY

The DeMi mission, a 3U CubeSat launched on an ISS resupply orbit, will demonstrate the use of MEMS deformable
mires and simple wavefront sensing algorithms. DeMi will image the ISS and other bright stars in different geometries that involve both longer and shorter paths through the atmosphere. In addition to the effects of the change in atmospheric volume on the image, DeMi includes a simple resistive heating element to intentionally introduce small thermal distortions in the aperture so that their effects can be captured by the wavefront sensor and wavefront corrections applied using the MEMS deformable mirror.

VI. BIBLIOGRAPHY


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BIographies

Kerri Cahoy received a B.S. in Electrical Engineering from Cornell University in 2000, an M.S. in Electrical Engineering from Stanford University in 2002, and a Ph.D. in Electrical Engineering from Stanford University in 2008. After working as a Senior Payload and Communication Sciences Engineer at Space Systems Loral, she completed a NASA Postdoctoral Program Fellowship at NASA Ames Research Center and held a research staff appointment with MIT/NASA Goddard Space Flight Center. She is currently a Boeing Assistant Professor in the MIT Department of Aeronautics and Astronautics with a joint appointment in the Department of Earth and Planetary Sciences at MIT.
Anne Marinan earned her B.S. in Aerospace Engineering from the University of Michigan, Ann Arbor in 2011. She is a second year Masters’ candidate at the Massachusetts Institute of Technology in the Space Systems Laboratory and associated Wavefront Control Laboratory. Her research interests include systems-level analysis of designing constellations of CubeSats and applying adaptive optics to space-based applications.

Caitlin Kerr will receive a B.S. in Aerospace Engineering from the Massachusetts Institute of Technology in 2015. She currently works as an undergraduate researcher in MIT’s Wavefront Control Laboratory.

Matthew Webber received a B.S. in Physics and Mathematics from Northeastern University in 2012 while doing research at Draper Laboratory and the Harvard-Smithsonian Center for Astrophysics. Matthew is currently pursuing a PhD at Massachusetts Institute of Technology in planetary science, researching exoplanet detection, astrophysics, and astrobiology.