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Calibration and Testing of the Deformable Mirror Demonstration Mission (DeMi) CubeSat Payload

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ABSTRACT

The Deformable Mirror Demonstration Mission (DeMi) is a 6U CubeSat that will operate and characterize the on-orbit performance of a Microelectromechanical Systems (MEMS) deformable mirror (DM) with both an image plane and a Shack-Hartmann wavefront sensor (SHWFS). Coronagraphs on future space telescopes will require precise wavefront control to detect and characterize Earth-like exoplanets. High-actuator count MEMS deformable mirrors can provide wavefront control with low size, weight, and power. The DeMi payload will characterize the on-orbit performance of a 140 actuator MEMS DM with 5.5 μm maximum stroke, with a goal of measuring individual actuator wavefront displacement contributions to a precision of 12 nm. The payload will be able to measure low order aberrations to $\lambda/10$ accuracy and $\lambda/50$ precision, and will correct static and dynamic wavefront phase errors to less than 100 nm RMS. The DeMi team developed miniaturized DM driver boards to fit within the CubeSat form factor, and two cross-strapped Raspberry Pi 3 boards are used as payload computers. We present an overview of the payload design, the assembly, integration and test progress, and the miniaturized DM driver characterization process. Launch is planned for late 2019.

INTRODUCTION

The Deformable Mirror Demonstration Mission (DeMi) is a CubeSat technology demonstration mission to provide on-orbit data for a Microelectromechanical Systems (MEMS) Deformable Mirror (DM). MEMS DMs are a promising technology proposed to enable the precise wavefront control required for future exoplanet direct imaging space missions.

Direct imaging can enable detailed characterization of exoplanets by gathering astrometric and spectroscopic data to study exoplanet orbits and atmospheres.[1] Coronagraphic instruments are used to block the light of the star so the dim planet can be resolved. This technique requires precise control of the optical system. For instance, resolving an Earth-like planet orbiting a Sun-like star requires contrasts of 10^{-10} which translates to picometer-level control of the optical wavefront.[2] Adaptive optics systems enable this level of control by measuring optical aberrations and controlling a deformable mirror to correct them. Adaptive optics systems are used for ground telescopes to correct for atmospheric turbulence[3] and are proposed for future space telescopes to correct for thermal and mechanical effects in space.[4] MEMS DMs are a promising technology for space-based adaptive optics because of their small size, high actuator density, and low power requirements.[5]

MEMS DMs are batch manufactured out of layers of conducting and insulating polysilicon films and then selectively etched to form individually addressable actuators. The DeMi mission will fly a Boston Micromachines Corporation (BMC) continuous facesheet MEMS DM with 140 electrostatically controlled actuators. A BMC MEMS DMs was at least briefly powered and actuated in near-space on the Planet Imaging Coronagraphic Technology Using a Reconfigurable Experimental Base (PICTURE-B) sounding rocket mission.[6] Other types of optical MEMS devices have flown at high altitudes or in low-Earth orbit, such as a micromirror on the MEMS Telescope for Extreme Lightning (MTEL) satellite[7] and the microshutter array for the Far-UV Off Rowland-circle Telescope for Imaging and Spectroscopy (FORTIS) sounding rocket mission.[8]

The goal of the DeMi mission is to raise the Technology Readiness Level (TRL) of MEMS DMs from 5 to at least 7. The key payload requirements are to measure individual DM actuator wavefront displacement contributions to a precision of 12 nm, measure low order optical aberrations to $\lambda/10$ accuracy and $\lambda/50$ precision, and correct static and dynamic wavefront errors to less than 100 nm root-mean-square (RMS) error.[9] The DeMi mission will demonstrate that MEMS DMs can survive the vibrational, thermal, and radiation effects of launch and long duration operations in space.[10]

PAYLOAD OVERVIEW

Optical Design

The DeMi payload design is described in detail in Allan *et al.* 2018[11] and briefly summarized here. The DeMi optical design is essentially a miniature space telescope with an adaptive optics instrument, but without a coronagraph. The primary mirror is a 50 mm off axis parabola (OAP) that focuses external starlight light onto a field mirror, where an internal calibration laser source is injected. The light from either an external target or the internal laser calibration source is collimated by another OAP and then reflects off of the 140-actuator continuous facesheet BMC MEMS DM. A beamsplitter splits the light. Half of the beam is focused onto an image plane wavefront sensor (WFS), which measures the point-spread function (PSF) to monitor the wavefront correction and measure tip-tilt errors. The rest of the light bounces off of a pair of relay OAPs and is measured by a Shack Hartmann WFS, which uses a lenslet array to focus the light into spots on the detector and measures the spot displacements to calculate the shape of the wavefront. The Shack-Hartmann wavefront sensor uses the Moore-Penrose pseudoinverse approach to perform zonal reconstruction of the wavefront. Figure 1 shows the DeMi optical design with the ray trace overlaid.

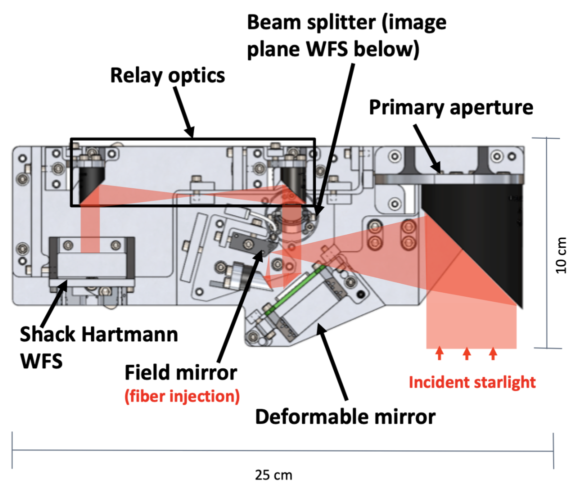

Figure 1: DeMi optical design with ray trace overlaid in red. Figure reproduced from Morgan et al. 2019.[4]

Concept of Operations

The DeMi payload has two operational modes, one that looks at an internal calibration target laser source, and the other that looks at external astronomical sources, *e.g.*, star targets. To observe external star targets, the spacecraft will slew to point at a star and use the image plane WFS for closed-loop control of the DM to correct tip-tilt errors. The PSFs collected by the image plane WFS will be used to collect photometric measurements of stars with V band magnitudes less than 3. The internal laser calibration source will be used to measure the performance of the DM over time by poking each actuator and measuring the resultant wavefront on the Shack Hartmann WFS. The internal laser calibration source will also be used to demonstrate wavefront control using the Shack Hartmann WFS for closed-loop control of the DM while measuring the PSF on the image plane WFS to monitor the results. The DeMi concept of operations is summarized in Figure 2.

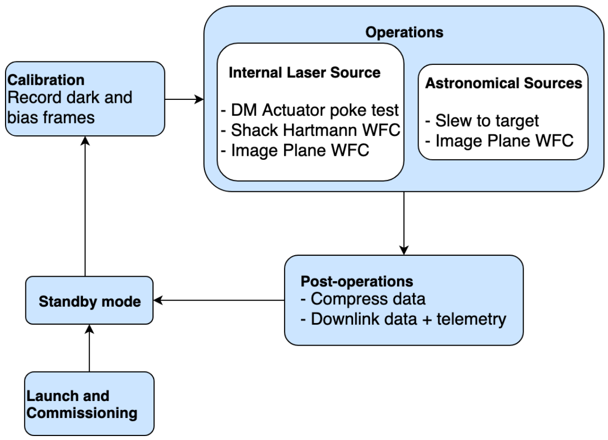

Figure 2: Summary of DeMi payload concept of operations.

Uplink of spacecraft and payload commands, and downlink of telemetry and science data will be accomplished through the use of two different RF communication links. The primary Telemetry, Tracking, and Control (TT&C) link will use an Astrodev Lithium 2 Radio (Li-2) on the spacecraft, and another Li-2 radio that is integrated into the UHF ground station on the MIT campus in Cambridge, MA. This primary TT&C link will operate at 9600 bps, with an uplink frequency of 449.75 MHz and downlink at 401.3 MHz. It and will primarily be used for commands and housekeeping telemetry. The high-rate data downlink will use a Cadet-U UHF radio, manufactured by the Space Dynamics Laboratory (SDL), and will use a ground station at the NASA Wallops Flight Facility. This link will operate at 3 Mbps, with uplink at 449.75 MHz and downlink at 468 MHz. The high-rate capability will be used to downlink images and wavefront sensor data from the payload, as well as large blocks of payload and bus telemetry.

Command and control capability is implemented with Blue Canyon Technologies (BCT) extension of the Ball Aerospace COSMOS ground station software, provided with a software bridge to interface with the Li-2 transceiver. Commands implemented in COSMOS include both direct and scheduled actions for each the satellite bus as well as the DeMi payload itself, passed through by the bus. Commands in each segment are implemented as CCSDS telemetry and command packets, with messages sent directly to the payload wrapped in with a secondary header for delivery. Scheduling of observation sessions is done by commanding the bus to point to a target star once the spacecraft and payload are in the external observation configuration. The bus is also commanded to boot and configure the payload for the observation. The payload's subsequent actions are automated; cues from timed commands from the bus to payload indicate coarse pointing error as the bus pointing settles on the target. The payload may issue corrective pointing commands to the bus for fine adjustments of accumulated tip or tilt error observed by the payload.

Operator commands to the bus also include initiating downlink of buffered telemetry and data packets from the payload. Downlink scheduling requests indicate whether the the Cadet radio or the TT&C Li-2 are to be used in advance of the downlink to allow for buffering of data to the correct radio. Ground commands passed directly to the payload will be primarily used for configuration adjustments and requesting specific portions of the payload data for downlink.

CCSDS File Delivery Protocol (CFDP) is not available on the DeMi bus. File uplink is provided as an extension to the existing command packet. Files such as subprocess executables or configuration file replacements are packetized to no larger than 65535 Byte segments per the Space Packet Protocol.[12] Upon receipt by the payload, the segments are verified against included checksums, saved, and reassembled. File downlinks use fragmentation and reassembly on the ground. Both ground-side fragmentation and reassembly use Python scripts developed outside of COSMOS. COSMOS is used to form headers and record transmission/receipt of packets being via COSMOS. Information about the available data onboard that has not yet been downlinked is provided in a predefined file that is regularly updated. The file informs operators of the range of available data for downlink.

Electronics Design

DeMi Payload Electronics Stack The payload electronics stack uses a set of redundant payload computers (PLCs), dual high-voltage driver boards for the DM, and a power distribution board. There are also interfaces for control and feedback from the DM, both payload imaging sensors, and the internal laser control source. Power is sourced from the BCT satellite bus, which also provides data interfaces for each of the PLCs. A high-level diagram summarizing the DeMi electronics system is shown in Figure 3.

The stacking form factor of the payload electronics is inspired by CubeSat form factors but the footprint is constrained to 80 mm × 80 mm by the DeMi optical system and satellite bus layout. Due to this size constraint and the high number of interface and control lines between the boards, the high-density/low-profile 100-pin Samtec LSEM-series hermaphroditic mezzanine connector was selected for interfacing between all boards, with varied heights to accommodate components on each board.

Dual PLCs provide resiliency and share access to all interfaces in the stack such that either can execute the core functionality of the demonstration. Each PLC can control the deformable mirror via the driver boards, and each has access to one of the imaging devices. Though the imaging devices are configured for different wavefront sensing approaches, the functionality of the DM can be assessed using either.

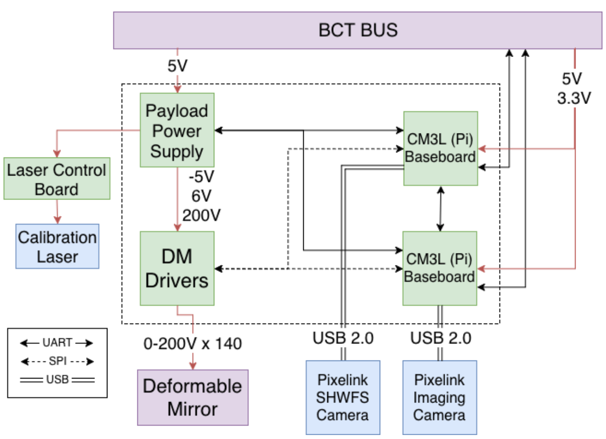

Figure 3: DeMi payload electronics system diagram.

Payload Computer (PLC) Board

The payload computer board has interfaces for the Raspberry Pi Compute Module 3 Lite (CM3L) computing platform. The board provides the following interfaces: independent UART, as well as 3V3 and 5V power interfaces to the satellite bus; USB 2.0 via Samtec T1M-05 to host the Pixelink PL-D775; dual micro-SD card spring-less interfaces; the SODIMM slot to host the CM3L; top and bottom hermaphroditic mezzanine connectors to pass all stack-interfaces to (or receive from) the companion PLC board. The stack-interfaces include multiple SPI interfaces and control lines to the deformable mirror high voltage driver boards, UART interfaces to each the power board MCU as well as the accompanying companion PLC, and internal laser source control. This configuration isolates power and ground, which is provided directly to each PLC from the satellite bus, with a shared reference. To accommodate this, as well as the higher TTL 6V of the driver boards versus the CM3L's 3V3 maximum, a pair of 6-channel unidirectional isolators limits all incoming signals from other boards, as well as key outgoing signals.

The primary CM3L UART "PL011" is used for the dedicated 115200 baud data interface with the satellite bus, connected by an Omnetics Nano-D very low profile 9 pin connector. The "mini UART" is reserved as a debugging interface. The two remaining UARTs to the power MCU and the companion PLC are implemented as software UARTs at a lower 9600 baud.

The 3V3 power source from the satellite bus is provided directly to all associated components with the following exceptions. The USB PL-D775 interface is the sole load on the 5V source on each PLC board, enabled by a CM3L-controlled load-switch. The CM3L needs a 1V8 power input as well as the direct 3V3; this is stepped down on the PLC board from the 3V3 rail. Each SD card is operated independently and is enabled by load switches on the 3V3 rail. The ADM6316 watchdog timer (WDT) low-voltage reset is softened by a Schottky diode and capacitor, isolating it from sudden CM3L current draw increases which it is sensitive to.

The PLC implements a reset-and-failover scheme in recognition that each the CM3L and micro-SD cards from which it boots are COTS components with possible failure modes. While an industrial-rated micro-SD card is used, high-current-draw failure modes which may cause permanent flash failure are mitigated via fast-shutdown current-limited load switches. Reset indicators from these load switches are one of two reset conditions observed by this circuit. The other is the GPS PPS provided by the satellite bus data interface. Suppressible by the satellite bus, the PPS serves as a directly controllable reset function via ground commands and reset conditions provided to the satellite bus. In either of these reset conditions, the hardware reset sequence is triggered by the external watchdog timer: the output toggles the CM3L's reset ("run") input directly while simultaneously flipping a JK-flipflop in toggle mode to its opposite value. The opposing outputs of this toggle control each of the micro-SD cards in opposite fashion, and the positive output also controls the 5-channel SD-mux. When the toggle flips during a reset, it causes the next boot to be from the other micro-SD card, safeguarding the system from becoming stuck booting from a potentially corrupted micro-SD card. Resets are accounted for by the payload software and can be triggered internally to reattempt booting from the prior micro-SD when appropriate. Note the WDT's output to the CM3L reset must be made via a noninverting buffer to prevent the internal capacitance of the CM3L "run" pin from slowing the rise of the line voltage below the minimum slew rate required by the flipflop's input.

High Voltage Driver 32-channel Unit

The original DM driver electronics from BMC were too large to fit on the DeMi mission, so a COTS-based miniaturized DM driver was developed as described in Haughwout 2018.[5] The final design consists of three 80 mm × 80 mm × 10 mm circuit boards and is shown in Figure 5.

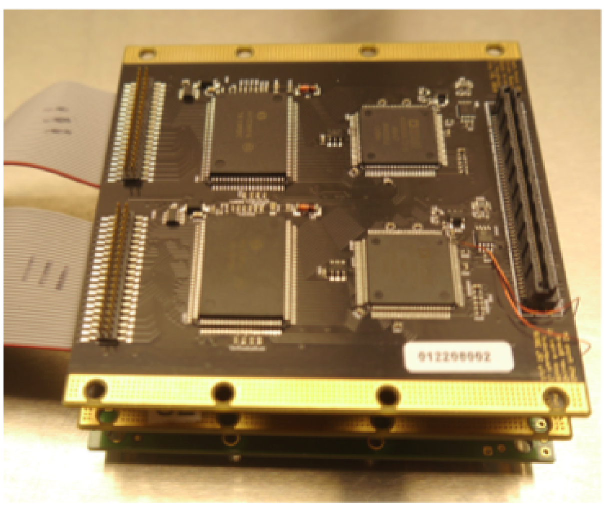

Figure 4: Miniaturized DM driver electronics. Each board is 80 mm × 80 mm × 10 mm. Third driver DAC/Amplifier unit on opposite side of each board. Each driver board has 70 output channels with 14 bits of resolution from 0 to 200 Volts. PLC boards not shown, reside on top of stack, with power board opposite on bottom of stack.

Built around the AD5382 DAC and the HV256 high voltage amplifier (32-channels each), a single DeMi driver "unit" provides 32 controllable channels. These channels are aggregated in sets of three per driver board. The channels are controlled by a SPI interface to the DAC. The AD5382 utilizes additional control signals to standard SPI not shown. The SPI clock, data, and additional control lines are

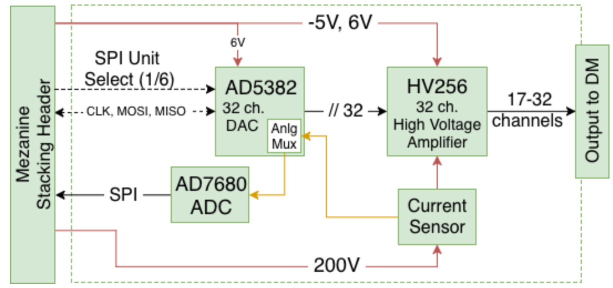

Figure 5: DM driver electronics functional diagram with key DAC/Amplifier components. Three instances of this "unit" are populated on each of the two driver boards. Figure reproduced from Morgan et al. 2019.[4]

shared between all six driver units on both boards, forming a shared bus between the drivers and the PLCs. Excluded from this shared bus is the control-select line (termed "SYNC" on the AD5382), for which an independent control line is provided to the DAC of each unit. Care must be taken not to exceed fan-out limits of the SPI pins as units are added, but no fan-out buffers were needed for the configuration presented. The shared bus pins can be passed all the way through the stacking mezzanine, but the independent SYNC lines must be deconflicted between boards by staggering the pin connections to allow the control to pass through one board to reach the other, yet present all control lines to the PLCs at once.

An ADC interfaced via SPI is also provided in each unit. While it could have been combined with the DAC SPI, it is separated to isolate risk of conflicts with the DAC which is of foremost importance. The interface for the ADC of each unit is combined with the other units as a bus with offset control lines in the same manner as the prior interface described. The ADC's source input is the single analog output from the AD5382's analog mux, which provides configurable output sourced from any of the DAC's 32 channels, as well as 4 additional mux external inputs. An external input for each unit's AD5382 analog mux is populated by the output of a current sensor configured to monitor a shunt on the high-power input to the HV256. This current sensor allows monitoring of the HV256's consumption, which varies predictably with channel output level. In the case of actuator failure, current consumption can be used to corroborate a diagnosis if the failure is electrical in nature.

INTEGRATION AND TESTING

Engineering Model

The DeMi payload is in the integration and testing stage at MIT. The MIT team has assembled and aligned a full flight-like Engineering Model (EM) for end-to-end system testing. Assembling the EM served as a dry-run to test assembly procedures for the flight model. In the process of assembling and aligning the EM minor mechanical modifications were made and implemented for the flight components to improve the flight integration process.

We aligned the engineering model (EM) payload optics using a Zygo interferometer. The engineering model payload was aligned so that the dominant aberrations as measured at the SHWFS location were -0.492 waves of focus and 0.218 waves of astigmatism. However, after this alignment procedure was completed, the DM was removed in order to place a protective cover on it before placing it back into the payload, and the alignment of the EM has degraded as a result. The screws were torqued to the appropriate values with a torque wrench throughout the alignment process, and after alignment was completed, the screws were staked in place with 3M Gray 2216 epoxy. The full aligned EM optical bench is shown in Figure 6. Alignment of the flight model is underway and should reach a similar level of alignment. We do not plan on removing the DM before staking the payload in its final configuration.

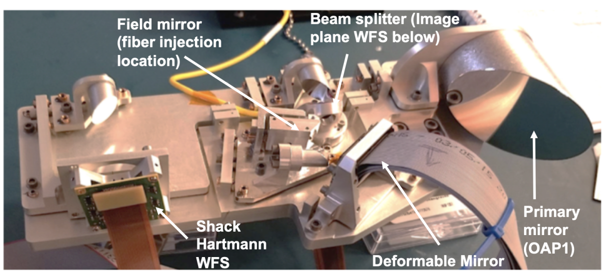

Figure 6: Aligned DeMi Engineering Model optical bench. Figure reproduced from Morgan et al. 2019.[4]

Miniaturized DM Driver Testing

The DeMi team has conducted testing of the miniaturized DM driver electronics with a Zygo interferometer. In this test, the DM was mounted directly in front of the interferometer so the actuator displacements could be measured directly. The testing procedure began with taking a measurement with the DM powered on but unactuated to subtract from each actuated image to reduce noise in image processing. For each actuator, an interferometer measurement was taken with the actuator displacement set to 15% and 30% of the maximum voltage. Displacements higher than this could not be measured consistently by the interferometer. These measurements were analyzed by subtracting the unactuated measurement, cropping the measurement to the area surrounding the displaced actuator, and fitting a Gaussian to the measurement to compute the magnitude and width of the displacement. The mean displacement measured for 30 V actuation is 70 nm with a standard deviation of 15 nm while the mean displacement measured for 60 V actuation is 269 nm with a standard deviation of 18 nm.

A representative sample of the actuators were also measured with the Zygo instrument with the BMC driver for comparision. For 30 V actuation, the mean displacement was 88 nm with a standard deviation of 13 nm and for 60 V actuation, the mean displacement was 244 nm with a standard deviation of 9 nm. The variation in these values is likely due to measurement uncertainty in the interferometer. The miniaturized DM driver has been verified to operate properly. The EM has also been used to test the miniaturized DM driver electronics with the payload SHWFS as described in Morgan *et al.* 2019.[4]

CONCLUSIONS

The DeMi payload integration and testing is underway. The flight model is currently being assembled and aligned at MIT. The EM is still being used for worksmanship environmental testing evaluation and end-to-end payload operations testing. The next steps for the DeMi project are to complete flight assembly and alignment and integrate with the spacecraft bus. DeMi is expected to launch in late 2019. The flight results from this mission will provide useful data for future space telescopes that plan to use MEMS deformable mirror technology.

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