Army Cost Efficient Spaceflight Research Experiments and Demonstrations Attitude Determination Experiment

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ABSTRACT

Army Cost Efficient Spaceflight Research Experiments and Demonstrations (ACES RED) is an iterative, periodic flight experiment and demonstration effort to test singular phenomenologies, technologies, and concepts for future (S&T) projects that are directly related to and in support of the United States Army Space S&T Roadmap Programs. The first ACES RED experiment, AR#1, has a main focus to generously expand the available dataset to verify long-duration performance as well as mature various commercial-off-the-shelf (COTS) technologies that will reduce the cost and complexity while maintaining performance of Army small satellites. AR#1 has a primary focus on attitude determination and control components. The experiment will be mounted on the International Space Station with operation and access to continuous on-orbit data for greater than one year with reliable reference instrumentation.

INTRODUCTION

In the last 6 years, the Army has begun to recognize the potential of the small satellite platform, in particular the micro- and nano- classes.[1] On December 8, 2010, the U.S. Army Space and Missile Defense Command / Army Forces Strategic Command (USASMDC/ARSTRAT) deployed the Army's first wholly-owned and operated satellite in over 50 years, the SMDC-ONE 3U cubesat. The demonstration was launched on the first Space X Falcon 9 launch vehicle COTS demonstration which put the SMDC-ONE in a very low orbit, but its 35 day orbital lifetime showed sufficient promise to open the door for more research and demonstration into small satellite platforms. After launching 10 more 3U cubesats (11 to date) and tentatively launching the Army's first microsatellite for electro-optical imagery[2] in late 2017, the small satellite movement continues to show promise for growing Army tactical capability. It has become increasingly clear that in order to support these programs and future similar programs that more in-house expertise and capability is needed. Out of this need, the ACES RED program was born. ACES RED has two primary functions: 1) to train entry to mid-level Army personnel through collaboration with USASMDC/ARSTRAT contractors as well as direct, hands-on software and hardware development and 2) to demonstrate novel functional components in support of USASMDC/ARSTRAT programs and ultimately bring down mission risk and cost. The program is broken into experiments that each are intended to provide experience and facilitate expertise in the primary functional areas of spacecraft design as well as mature technology readiness of future flight components for Army small satellites.

MISSION

The first experiment, AR#1, is called the ADACS Flyer experiment. The primary payload is an MAI-400 attitude determination and control system (ADACS). Secondary and tertiary payloads include: redundant FPGA flight computers, low cost flight computers (PicoZeds, Raspberry Pis), global positioning system, low cost camera, and various internal vehicle diagnostic sensors. Figure 1 shows a diagram of the space experiment configuration and its components. The twelve month long flight experiment is partitioned into multiple technical objectives including:

1. Attitude Determination
   1.1. Test and compare multiple position knowledge and attitude state sensors (GPS, GNSS, IMU, Sun/Star/Earth sensors, cameras,

magnetometers) singularly and in various combinations to provide multiple vector inputs for control algorithms

1.2. Compare position with STP provided GNSS position

1.3. Compare attitude (via quaternion) of the MAI-400 with star tracker, IMU, and IREHS sensor to the attitude of the STP provided star tracker pair

1.4. Test our own control algorithms using the sensors available

1.5. Compare attitude determination using external sensors vs the on-board MAI-400 sensors.

2. Insert Control Commands

2.1. Flight test and validate a complete 3 momentum wheel ADACS subsystem (custom MAI 400) capable of spin-up,

2.2. spin-down,

2.3. reverse spin,

2.4. and individual software control of each wheel from the ground; this is currently not available through commercial products

3. Observation of Vehicle Health

3.1. Measure changes in thermal,

3.2. mechanical vibration, stress on structure

3.3. and power consumption of ADACS subcomponents versus lifecycle

4. Assessment and Maturation of Components

4.1. Achieve full lifecycle testing of nanosatellite attitude determination and control subsystem components for long duration space missions longer than 12 months

4.2. Use flight data to validate exact duplicate engineering model unit on Flat-Sat Bench at USASMDC/ARSTRAT

4.3. Test industrial grade flight computers and memory

4.4. Test low cost CMOS imaging sensors

4.5. Increase TRL for components

4.6. Test using redundant low cost processors in place of a single, expensive flight rated processor

5. GPS Data

5.1. Measure position sensor and attitude determination sensor data continuously on orbit to map and improve current physical models of sensor performance and accuracy (IMU, GPS, GNSS, magnetometer)

5.2. Measure GPS performance and gather data while pointed off nominal position

6. Update Flight Software during Mission

6.1. Demonstrate capability to upgrade, change, and reinstall modified/new flight software from the ground during flight

The mission is manifested for launch around late 2018 and will go into Low Earth Orbit (LEO) on an ISS resupply mission. AR#1 is one experiment on the Department of Defense's Space Test Program's (STP) STP-H6 payload. STP-H6 will be mounted on the nadir, ram-facing side of the International Space Station for the entirety of the twelve month duration mission. ISS will provide continuous data and power to all of the experiments on STP-H6 which provides a unique opportunity for long duration testing of small satellite components. Consequently, AR#1 has many non-traditional components incorporated into the experiment to be tested and verified alongside more traditional counterparts.

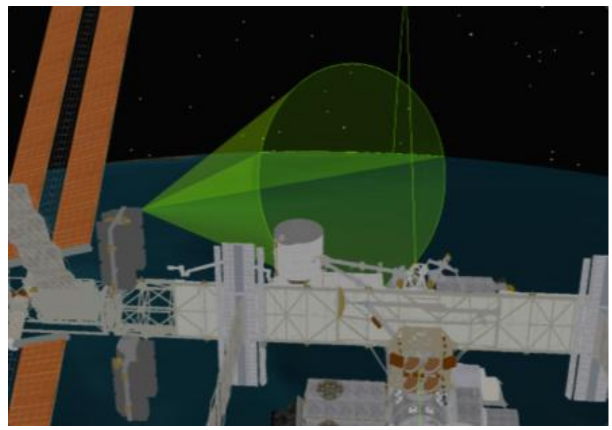

Figure 1: ACES-RED#1 Perspective

EXPERIMENT COMPONENTS

Modified COTS ADACS

The MAI-400 represents leading edge cubesat attitude determination and control technology offering substantial flexibility and capability, and has been employed in recent Army small satellite programs referenced herein. In an effort to validate the data collected in these programs as well as significantly expand the duration of the scope of data referenced data on orbit, the evaluation of this component constitutes the core technical mission of ACES-RED. The fully configured MAI-400 option leverages a suite of sensors including two IR Earth Horizon Sensors (IREHS), Magnetometer, Star Tracker, as well as actuation using three axes of reaction-wheels.[3] For the purposes of forward-looking evaluation and to accommodate safety requirements of the ISS host program, the MAI-400 model utilized by the AR#1 will feature a number of variations. Most significant is the inclusion of an integrated star tracker, for which power and volume accommodations must be made. In addition to the structural accommodations made for the additional sensor, enclosing material around the reaction wheels to ensure no debris material from a potentially fractured mass can possibly escape within the range of sizes specified as hazardous by NASA's safety mitigation requirements.[4]

AR#1 has been given the fortunate mounting position which yields a largely unobstructed field of view of the open sky. Coordinating with the STP-H6 team has allowed orientation of this star tracker to be coaligned with the STP-H6 standalone star-tracker, albeit with minimal translational offset. This view will change with the oscillations of the ISS and periodic operational maneuvers, but with careful planning and coordination will yield a generous flight-like dataset. Operation of the MAI-400 will be structured in order to maximize operational time, imposing periodic stress and idle modes to imitate a free flying satellite's concept of operations over the duration of the experiment. In addition to the planned concept of use mirroring, the actuators will be occasionally driven to saturation in order to carefully stress the capabilities of the system and evaluate potential on-orbit failure modes when the system fails to correctly orient itself (which will by necessity be the case when matched with the inertia of the ISS).

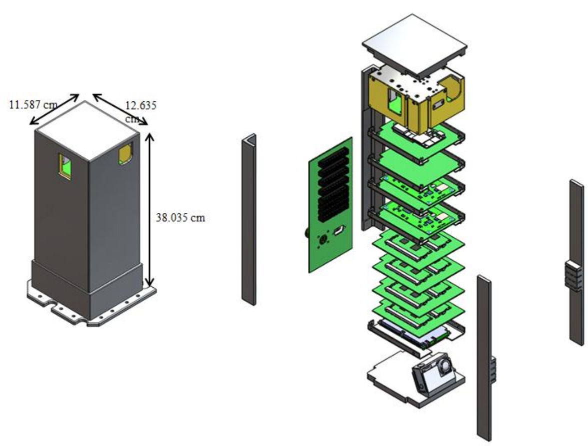

Figure 2: ACES-RED#1 Exploded View

The span of data collected on the performance and endurance of the MAI-400 actuators will be matched by the telemetry retrieved from the MAI-400's IREHS, Star-tracker, and magnetometer, as well as the H6-provided GNSS data, and the AR#1 GNSS, a NovaTel OEM628 with an off-nominal facing antenna (relative to H6's GNSS antenna). In addition to generating tightly configured, off-nominal antenna performance data, the experiment will benefit from a validated timing and positioning source against which the MAI-400's generated quaternions can be referenced. This data will help analyze and validate independently collected free-flight MAI-400 data. Additionally, this precisely timed position and orientation data will serve as a baseline and reference for analysis of the light-capture and imagery capabilities of the low cost camera as a star tracking sensor.

Low Cost Camera / Star Tracker Sensor

The AR#1 Low Cost Camera/Star Tracker experiment will utilize a GoPro Hero 4 Silver. The camera will be mounted inside the AR#1 experiment chassis in order to collect footage through a structural cut-away in an external wall with an embedded baffle. Long-duration exposure will be evaluated for light-capture ability and filtering techniques will be employed in post-processing efforts to minimize blur brought about by orbital motion during long-exposure image collection and optimize exposure length calibration. Once these datasets begin downlinking, immediate efforts to refine exposure calibration settings will allow on-orbit correction to maximize usable data collected. This imagery collected will be correlated with the timing, position, and attitude determination results yielded from the ADACS and GNSS devices described in the previous section. In this way, ideal results will be available to validate computed position and orientation if the imagery collected is suitable.

The maturation of the camera over a one year duration will be studied to determine the feasibility of using the Hero 4 silver on other small sat missions in the future. GoPro cameras have flown in the vacuum of space for short durations of time, as well as in the environmentally controlled habitat of the ISS. GoPros have been used extensively on high altitude balloon flights and suborbital rockets.[5] In March 2017, Astronauts Shane Kimbrough and Thomas Pesquet used a GoPro to document their 6½ hour space walk outside the International Space Station (ISS).[6] Flying a GoPro aboard AR#1 is different in the duration of the mission and purpose under evaluation. No accounted record of a long duration external GoPro mission has been found and AR#1 intends to determine how the GoPro Hero 4 Silver will perform over the year-long mission, and in doing so evaluate it for survivability and capability.

Given the 6½ hour spacewalk it has endured and its general use within the habitat, it is asserted that the electronics can withstand the vacuum of space and the high temperature fluctuations over several orbits. The unit will be evaluated for response to radiation accumulation in both data quality and overall survivability. The internal circuits of the Hero 4 are covered by a plastic casing which will offer little protection from any large amounts of radiation, but it will receive comparable shielding to the rest of the components provided by the AR#1 chassis. The year long mission offers ample opportunity to experience a total ionization dose (TID) characteristic of small satellite missions in LEO.

In the 6½ hour space walk, the GoPro would have experienced four complete orbits. This demonstrates the ruggedness of the GoPro as it survived temperature fluctuations of over 200 degree Celsius variation.[7] Over the 1 year mission of AR#1, the Hero 4 Silver will experience thousands of these temperature fluctuations. The difference in how well the camera withstands four orbits versus thousands of orbits is critical to understanding the suitability of the camera for other long term missions as a primary sensor. Temperature fluctuations over long durations can cause structural warping as well as affect the internal electronics, but operational damage can be mitigated by overheating-shutoff protection features built into the GoPro's firmware. AR#1 will be able to collect data to discover if the camera can withstand the varying stress over time.

There are two primary structural concerns to be determined on the AR#1 mission; Structural Warping and Solder Whiskering. The case of the Hero 4 is made of plastic. The question arises, will this plastic deform over the temperature fluctuations of thousands of orbits? The GoPro will not be manually operated, and pressing buttons or human handling is not an issue. However, deformation could cause changes in the method of which the camera is mounted should an extreme temperature cause cracking or melting around mounting locations, or permanent warp. As the lens and electronics are held in place by their case, potential shifting, bending, melting and warping may be inferred by atypical translation of the collected images, or result in failure in more extreme cases.

Solder whiskers are an anomaly in which tin based solder grows conductive crystal structures. The whiskers can cause electrical shorts and severely damage sensitive electronic components. Eutectic tin based solders will not grow these whiskers[8], but as the Hero 4 Silver is a Commercial Off the Shelf (COTS) component, such adjustments to manufacturing are not feasible. The one year duration will provide justification for the survivability, given such risks, on future missions.

Flight Computers

The core of both the Q7 and PicoZed is the Zynq-7000, a Xilinx chip series with an ARM processor integrated directly with the programmable logic of an FPGA. The Xiphos Q7 system implements a reliable and recoverable FPGA processing environment utilizing a Xilinx Zynq-7000 series chipset made configurable for end use and an Actel ProASIC3 which implements recoverability and reprogram-ability functionalities leveraging triple-modular redundancy (TMR) strategies to ensure its own robustness, as well as error detection and correction (EDAC) methods for integrity of RAM from which the Zynq configuration can be reloaded.[9] In this manner it indirectly extends the robustness of the ProASIC3 to the Zynq. Where prompt recovery is an acceptable alternative to extremely high reliability, this methodology provides implementation flexibility to the system designer that would otherwise be limited to rad-hard FPGAs for the entire system implementation.

Additionally AR#1 will fly secondary flight computers including the Avnet PicoZed, offered as an industrial grade system-on-module built around the Zynq-7000, evaluated for broader acceptable temperature ranges than its commercial rated counterpart. The Zynq-7020 variant is selected to match the Zynq variant on the Q7. At two orders of magnitude less expensive than high reliability Zynq-centered systems, the PicoZed hosts a densely packed set of features. Though the primary component is the same, the PicoZed is not designed as space system solution, and lacks features commonly associated with space-rated components, such as TMR, memory-scrubbing, rad-tolerant components.[10] Given typical LEO radiation rates and common failure rates due to TID even for components with higher tolerance,[11] failures are anticipated during the duration of this mission. To account for and evaluate these effects, AR#1 will operate multiple PicoZeds, along with other non-FPGA secondary flight computers, in a semi-redundant configuration where each flight computer will duplicate the functionality of the other flight computers. The Q7 is given ultimate authority of scheduling which flight computer other than itself will be allowed to drive the system at large such that performance can be evaluated without jeopardizing the mission. In this way, a direct comparison of the advertised advantages of the Q7 will tested relative to the same chipset and same system implementation as the industrial grade equivalents. Zynq FPGAs are susceptible to corruption in configuration bits and RAM, as well as in-circuit transient pulses.[12] The former two issues can be mitigated with memory scrubbing and EDAC techniques, respectively,[12] methods which are employed on the ProASIC to ensure the integrity of its own configuration and the baseline with which the Zynq would be reloaded given a failure.

Xiphos Q7 system was also selected for unique features provided including multi-mode peripheral availability such as native implementation of RS-422, efficient on-board power regulation, and customization ability. It is worth noting that this ability for significant customization should be a cause for great care to be taken when evaluating the performance of this system in different system implementations.

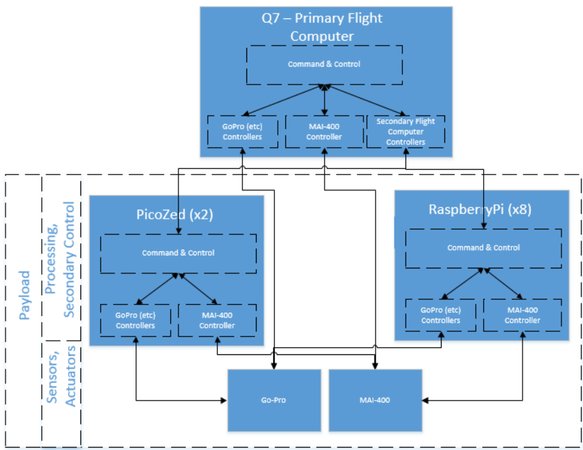

Figure 3: ACES-RED#1 Redundant Control

Flash Memory

Use of consumer and industrial grade flash memory in support of small satellites has been undertaken as a risk necessitated by the budget and size constraints. AR#1 seeks to validate industrial-grade Secure Digital (SD) non-volatile flash memory cards as sufficiently stable memory storage devices when used in the configuration presented. Further, a redundant control methodology is employed to leverage the parallel and redundant nature of the AR#1 computational payload. In addition to the primary (Q7) and secondary (PicoZed) flight computers described in the previous flight computer section, RaspberryPi Compute modules will be arranged in an array of no less than eight Computes grouped each two per carrier interface card. Each carrier interface card facilitating the interface to the other subsystems and control by the Q7 primary flight controller, will also serve as host for the memory under test. Outfitted with redundant USB-protocol peripheral integrated circuits, the Computes will each host four SD memory devices. Each of these SD memory devices will be cross connected via its USB interface IC such that failure risk of one Compute can be mitigated by the second Compute assuming control of its SD devices in such an event as an unrecoverable failure. Assessment of the SD devices health will individually evaluated by writing known patterns to the flash memory and executing scrubbing exercises in the Compute software.

CONCLUSION

The ACES-RED program provides unique and crucial hands-on experience for the current generation of entry to mid-level Army engineers. Additionally, the Army warfighter needs of increased data throughput, extended global coverage for communications and data, and new and novel strategic and tactical capabilities are ever growing. Many of these needs will be met by future Army small satellite capabilities. USASMDC/ARSTRAT's ACES RED program is investigating and maturing technologies to enable these future satellites. Specifically, AR#1's focus on attitude determination and control provides the next step in developing small spacecraft capable of the attitude stability and control needed to provide for the future warfighter's needs. Furthermore, the novel flight computers, processor architecture, fall-over strategy, and sensor suite have the potential to drastically decrease costs of future missions while maintaining these capabilities.

Acknowledgments

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