Summary of Measurement of Actuator Response In Orbit (MARIO) Spacecraft and Experiment

Prepared For
The United States Federal Communications Commission

Prepared By
Dr. James W. Cutler, Dr. Daniel Inman, Matthew Szczerba, and Paul Knudsen; University of Michigan
Dr. Robert Owen, Extreme Diagnostics

Abstract

Measurement of Actuator Response In Orbit (MARIO) is a nanosatellite-based technology demonstration experiment developed at the University of Michigan for Extreme Diagnostics in collaboration with NASA LaRC and NASA JPL. The mission's objective is to increase the technology readiness level of macro-fiber composite based actuators by monitoring their health and performance throughout a prolonged period of exposure to the low Earth orbit environment. The MARIO experiment is hosted on a 3U CubeSat called MC9, developed at and operated from the University of Michigan.

Background

MARIO is a cubesat-based technology demonstration of active submicron optomechanical control for robotic assembly of large telescopes using piezoelectric actuators. MARIO matures this technology to technology readiness level (TRL) 8/9 through closed loop control demos based on Macro Fiber Composite piezocomposite actuators. Macro Fiber Composites are rugged piezoelectrics developed by NASA specifically for space applications.

Macro Fiber Composite Materials

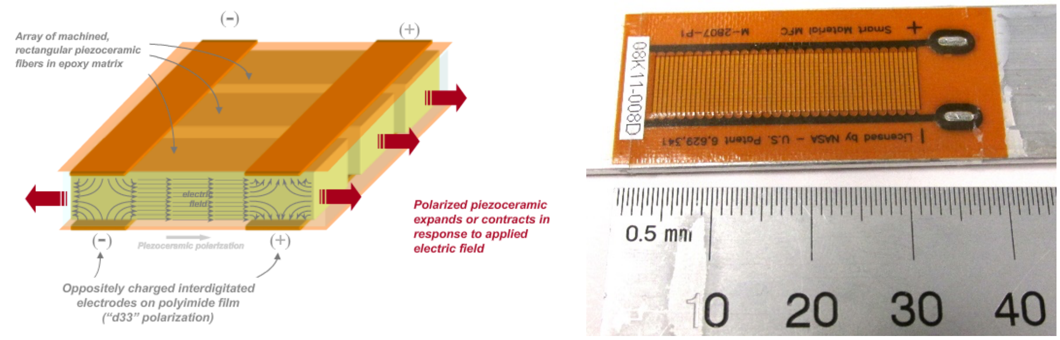
The real-world use of piezoelectric actuators is plagued by their well-known brittle fracture mechanism[1]. NASA researchers overcame this problem by developing a new generation of piezoelectric actuators – one based on interdigitated electrodes connecting piezoceramic fibers embedded in an epoxy matrix. This geometry increases in-plane strains, overcomes the piezoelectric fracture problem, and creates a reliable device referred to as a Macro-Fiber Composite (MFC)[2]. MFCs have been increasingly proposed as actuators in active space structures. However, further work is needed to fully understand all their capabilities and limitations in real-world space operations. The NASA team that developed MFC materials was led by Dr. W. Keats Wilkie, who was the primary inventor. Dr. Wilkie provided his extensive expertise to MARIO throughout satellite construction by helping to guide MARIO tests and experiments and developing links to specific NASA needs and objectives. Figure 1 illustrates the schematics of MFC components.

Relevant Prior Work

MFC piezocomposites were successfully flown aboard STS-123 in 2008, but only in a shielded enclosure inside the Shuttle cargo bay and only for a relatively short duration (< two weeks).

---

[1] Freiman, S. W., L. Chuck, J. J. Mecholsky, D. L. Shelleman and L. J. Storz (1986) "Fracture mechanisms in lead zirconate titanate ceramics," Fracture mechanics of ceramics 8(1): 175–85.
[2] Wilkie, W. K., R. G. Bryant, J. W. High, R. L. Fox, R. F. Hellbaum, A. Jalink Jr., B. D. Little and P. H. Mirick (2000) "Low-cost piezocomposite actuator for structural control applications," Proc. of SPIE Vol. 3991(1): 323–34.



(a) (b)

Fig 1. (a) Schematics of the Macro-Fiber Composite. (b) MFC patch from Smart-Material®.

Preliminary tests were also briefly (1-hour) conducted in a near-space balloon flight[3]. Phase I of MARIO work established flight feasibility using the same techniques to be validated in LEO to assemble mirror elements in ground-based tests. The MARIO team has analyzed the application and control of piezocomposite sensor/actuators in detail[4]. MARIO data establishes operational limits, determine long-duration environmental exposure performance trends, and evaluate thermal compensation options as required to advance this active optomechanical control technology to TRL 8/9 for space operations.

Potential Applications

Reliable optomechanical control is needed for active control of large deployable telescope observatories such as those required for the Wide-Field Infrared Survey Telescope (WFIRST) and the New Worlds Technology Development Program (coronagraph, external occulter and interferometer technologies). Other relevant structures include various large multi-layer structures, and solar arrays needed for 300 KW-1 MW class Solar Electric Propulsion (SEP) space vehicles. MARIO also supports other space science areas like instruments for astrophysics projects such as star shape missions utilizing Starshade technology. Potential customers include projects like the FIR, Large UV Optical Infrared, and X-ray Surveyors (Formative Era) and the Cosmic Dawn and ExoEarth Mappers (Visionary Era). Maintaining the shape of large, high-precision composite reflectors in space will be extremely difficult; active composite reflectors that can adjust their shape *in situ* to maintain required tolerances should be both cheaper and considerable lighter[5]. Thermally stable actuator materials may also be useful in certain ground-based telescopes like the Cerro Chajnantor Atacama Telescope. Because this technology can be used to monitor wind energy turbine blades, the MARIO project is directly related to renewable energy.

Other NASA applications include active shape distortion compensation in non-reflector surfaces, e.g., struts, bipods, etc., active Structural Health Monitoring (SHM) and specialized sensors. A mission-capable SHM system has applications like crew safety, deep-space missions, mass reduction, and lunar/Mars exploration. Targeted applications include sensors for the Orion MPCV and Composite Overwrapped Pressure Vessels (COPVs).

---

[3] Zagrai, A., B. Cooper, J. Schlavin, C. White and S. S. Kessler (2013) “Structural health monitoring in near-space environment, a high-altitude balloon test,” 9th International Workshop on Structural Health Monitoring, September 10–12, Stanford University.

[4] Owen, R. B., Gyekenyesi, A. L., Inman, D. J. and Ha, D. S. (2011) *Hardware specific integration strategy for impedance-based structural health monitoring of aerospace systems,* NASA/CR-2011-217153, Langley Research Center, Hampton VA 23681, NASA Technical Reports Server (NTRS).

[5] Bradford, S. C., G. S. Agnes, C. M. Ohara, F. Shi, L. D. Peterson, S. M. Hoffman and W. K. Wilkie (2012) “Piezocomposite actuator arrays for correcting and controlling wavefront error in reflectors,” 53rd AIAA Structures, Structural Dynamics and Materials Conference, DOI: 10.2514/6.2012-1743.

NASA Glenn personnel are making use of an EDI MFC-based sensor for COPVs testing. NASA Agencywide COPV users include the ISS, the Space Exploration/Flexible Path, and numerous planetary projects. SHM technology is central to commercialization efforts aimed at taking MFC materials beyond the limited market of space deployables. SHM addresses commercialization aspects of the SBIR program, is useful for alternative energy applications, and may well provide the most widespread commercial application of MARIO technology. MARIO supports NASA's ability to land humans on the Moon in 2024 and a sustainable presence on the Moon by 2028. MARIO provides risk reduction for Moon to Mars related programs.

Non-NASA applications include small aperture adaptive optics for nanosatellite-based Earth imaging firms like PlanetLabs and nanosatellite space telescopes like ExoplanetSat. Other relevant sources of commercial Smallsat optical data for advancing Earth System Science and applications for societal benefit include Planet, Spire Global, Maxar (formerly DigitalGlobe, Inc.) and Teledyne Brown Inc. DLR Earth Sensing Imaging Spectrometer (DESIS). These data sources open a variety of additional commercial applications.

Modern tactical aircraft and hypersonic vehicles encounter major thermal, mechanical and acoustic loads. A fundamental problem is the dependence of the deformation state of the structure (feedback effect) on these loads (heating, aerodynamic, acoustic)—this could be addressed by active control for jitter suppression. Customers include Boeing. Health sensing is important for reusable vehicles, which are subject to fatigue damage. SpaceX and others will need SHM to enable rapid launch, monitoring during flight, and post-flight assessment. Health sensing is needed to re-certify vehicles for their next flight. Other applications include Homeland Security structural analysis to mitigate threats (preparedness) and assess damage (response), smart structures, and SHM of civil infrastructures, land/marine structures, and military structures. Civil infrastructure includes wind turbines (alternative and renewable energy).

Payload and Experiment

While MFCs have flown to space before, their performance has not been quantified under minimal thermal protection or for extended periods of time exposed to the space environment. Data is needed to show the viability of piezocomposites as optomechanical control actuators under these conditions. MARIO will produce this data in low Earth orbit (LEO) by completing the following technical objectives.

1. Precision robotic deployment and manipulation of test beam support structures;
2. Sub-micron precision closed-loop control of active structures in space; and
3. Evaluation and analysis of actuator response, stability and performance in LEO.

MARIO is the first *long-term* (6-12 months) spaceflight validation for piezocomposite actuators and matures active optomechanical control technology scalable to 16 m class structures and above.

Novel Technologies

MARIO contains two novel technologies. The first is a submicron beam alignment measurement and monitoring module, and the second is a new launch survival and on-orbit structural deployment system. Both technologies are detailed in this section.

The MARIO active-structure payload module enables direct measurement and monitoring of structural deflection and control – in this case active structural manipulation is provided by MFC actuators. In the LEO flight mission, MARIO deploys two identical active test structures to provide redundancy. Each test structure is a beam fixed at one end; the free end motion and set point positioning is monitored with submicron precision. The MARIO system thereby monitors both stability and repeatability for MFC actuators performing precision closed-loop control operations and set point positioning in LEO. MARIO employs a linear quadrature encoder to calculate and monitor the active beam tip deflection. As Figure 2 shows, a basic quadrature encoder is composed of a light source, a detector, and a grated scale. The light source shines onto the grated scale which marks the position of the object and the detector captures it and encodes it into an analog or digital signal.

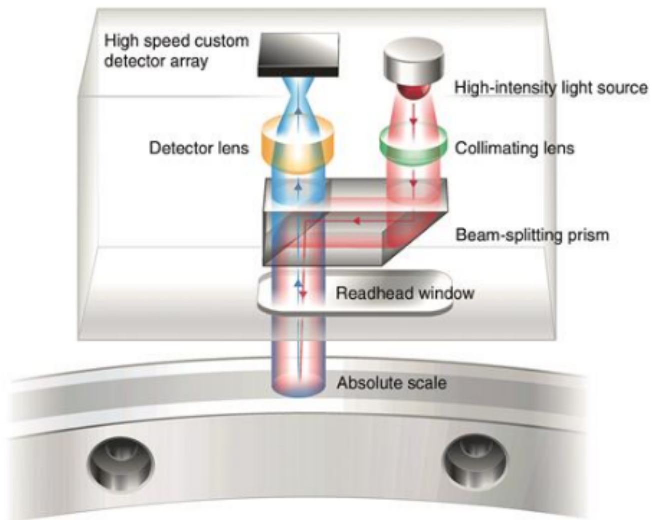


Fig 2. This figure shows how an absolute linear encoder works. It first directs light onto the absolute scale which is on the moving substrate. That light is then reflected back to the detector and encoded. The implementation on MARIO is slightly modified to minimize the encoder components attached directly to the moving tip[6].

Figure 2 shows a common optical encoder arrangement and illustrates functionality. MARIO uses a modified arrangement to minimize mechanical interaction between the encoder itself and the moving test beam tip. This system is based on a Renishaw magnetic linear quadrature encoder with reduced tip mass, which has a resolution of 0.25 µm. This component provides state of the art position sensing and assures highly repeatable position measurement under wide installation tolerances and temperature ranges. Operational temperatures range from -30° C to +85° C, which is well within the temperature variations anticipated for the MARIO LEO flight mission.

In LEO, active-structure launch survival and successful on-orbit deployment and operation are assured through a novel fixture that provides both secure mounting and high-voltage isolation and an advanced tie-down and deployment mechanism.

The two MARIO active test structures are bimorph actuators: that is, each identical structure is designed as a double layer element with two active layers and a passive layer between. In operation, one of the layers extends while the other compresses. As a result, this causes the element to bend. Launch survival and on-orbit deployment is complicated by the high-voltage nature of the MFC bimorphs. To deal with this MARIO incorporates the bimorph clamp design shown in Figure 3. The primary goals of the design are to provide secure bimorph mounting while ensuring total isolation of the high-voltage MFC terminals. Each high-voltage terminal is encased in an insulated chamber so that when fully assembled and clamped all high-voltage conducting surfaces are isolated and sealed.

---

[6] "Resolute UHV absolute encoder system with RTLA linear scale", Renishaw http://www.renishaw.com/en/resolute-uhv-absolute-encoder-system-with-rtla-linear-scale--18333 .

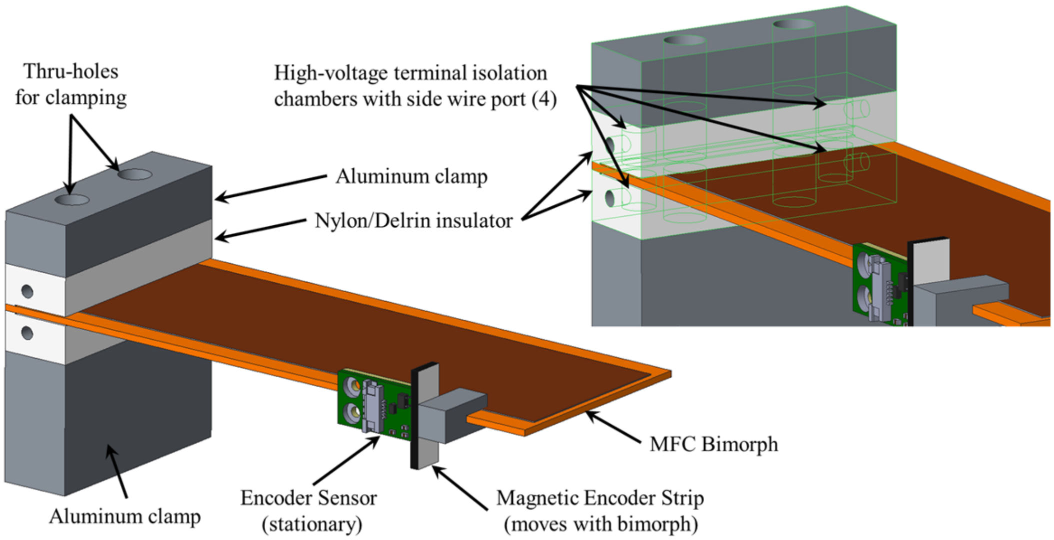


Fig 3. Detailed view of a single bimorph actuator showing clamp design and encoder mounting concept. This design ensures complete isolation of the high-voltage actuator assembly thus protecting the main satellite chassis from accidental high-voltage contact.

The actuation (active structure) experiment posed significant challenges to both payload integration and LEO operation. As the experiment measures the deflection of cantilevered beams, vibrational concerns arise. Specifically, the beam resonant frequency lies within typical launch vehicle profiles. That is, launch vehicle vibrational modes pose a direct threat to MARIO payload survival. Both beams must therefore be protectively stored for launch and deployed upon orbital insertion. MARIO's design for securing these beams for launch and subsequent deployment is based in part on a Naval Research Lab mechanism[7] composed of two rails and compressed springs. MARIO integrates this mechanism into a curved ramp structure that fits the active structure test beam and retracts a tie down wire.

In the launch-ready state, the beam is tied down to the ramp via this wire, which is wrapped around a burn resistor at the end of the ramp. The wire is under tension from compressed springs within the ramp's spring-rail mechanism. When ready to deploy, the burn resistor cuts the wire and the force of the springs retracts the wire back into the ramp's spring-rail mechanism. This arrangement has been tested extensively and ensures the payload will both survive launch vibrational stresses and deploy and function as planned in LEO. An image of the assembled mechanism in the launch-ready state is shown in Figure 4.

Payload Assembly

The MARIO payload containing the above technologies are packaged into a 1U enclosure along with power and control electronics developed by AVID Aerospace and the Michigan eXploration Laboratory, respectively. Images of the integrated payload are shown in Figure 5.

[7] Hartman, J. (2014, 09 03). *NRL Invents CubeSat Release Mechanism: To Deploy Solar Panels, Tethers*. Retrieved 04 12, 2017, from U.S. Naval Research Laboratory: https://www.nrl.navy.mil/media/news-releases/2014/nrl-invents-cubesat-release-mechanism-to-deploy-solar-panels-tethers.

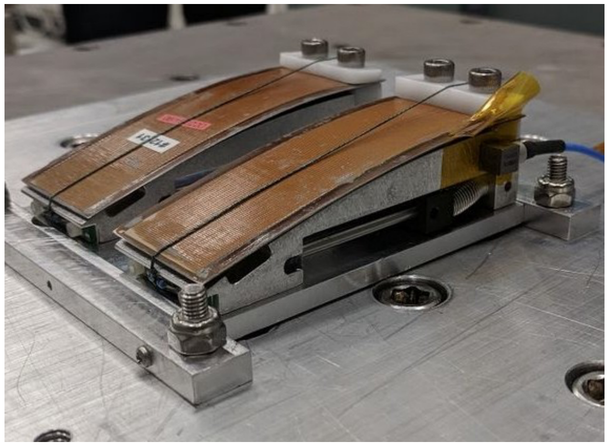
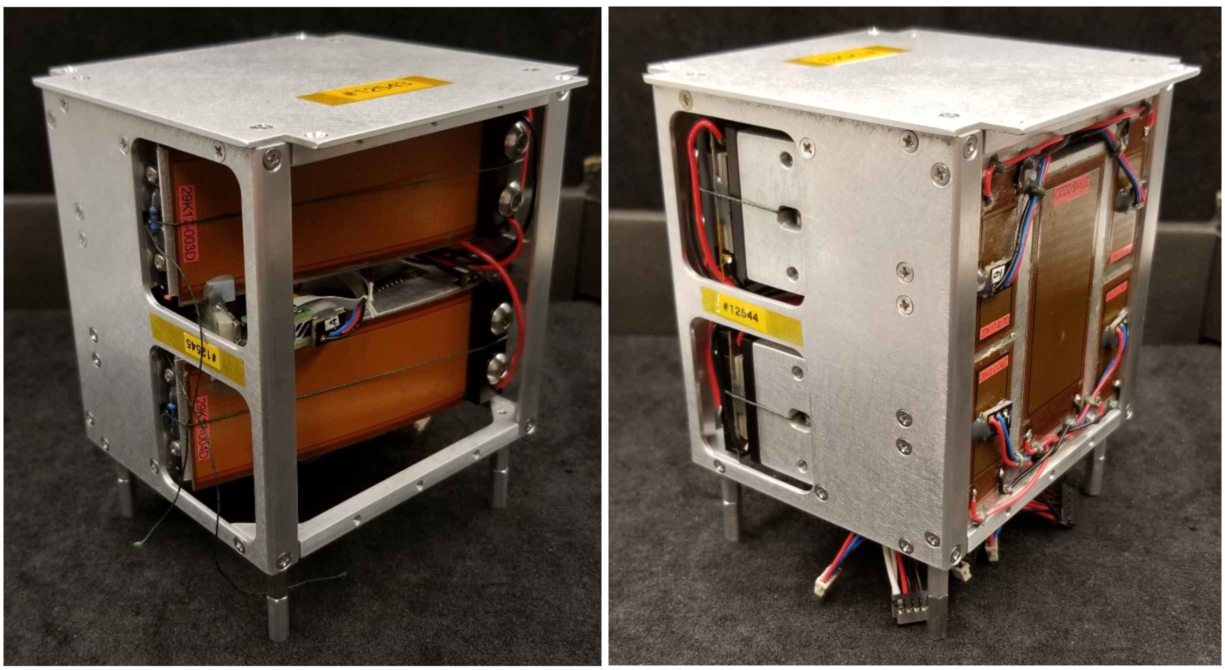


Fig 4. Experimental arrangement for bimorph release mechanism and vibration testing.



(a) (b)

Fig 5. MARIO payload engineering unit. The external MFCs visible in (b) are part of a previous version of the experiment and are not present on the flight copy of the payload.

Spacecraft

The spacecraft, which hosts the MARIO experiment, is a 3U CubeSat bus developed by the Michigan eXploration Laboratory based on its past 3U CubeSats such as the Radio Aurora Explorers (RAX) 1 and 2, the GEO-CAPE ROIC In-Flight Performance Experiment (GRIFEX), and the Tandem Beacon Experiment (TBEx).

The bus consists of a stack of electronic and magnetic components connected by wiring harnesses and held together by a pair of aluminum walls. Electrical power is generated by four fixed solar arrays on the long faces of the spacecraft and one small solar array on one of the short faces. This power is stored in a bank of lithium ion batteries and distributed to the flight computer, payload computer, payload, and sensors as necessary through a flight-proven[8] electrical power system developed at MXL.

The spacecraft employs passive magnetic attitude control to prevent tumbling of the spacecraft and to maintain a favorable set of orientations for communications. Communication with the ground is achieved through an AstroDev Lithium 2 radio at 437.485 MHz. Uplinks are encrypted and transmitted from a set of directional antennas at the University of Michigan, and unencrypted downlinks are broadcast for reception at the University of Michigan and nodes on the SatNOGS network[9]. These downlinks, being unencrypted, are accessible to amateur radio operators and space enthusiasts around the world, contributing to the open and educational nature of the license under which this spacecraft's radio operates.

A computer-generated drawing of MARIO is shown in Figure 6. Views of the engineering unit are shown in Figure 7. Figure 8 shows a computer-generated drawing of the antenna in its deployed and stowed configurations.

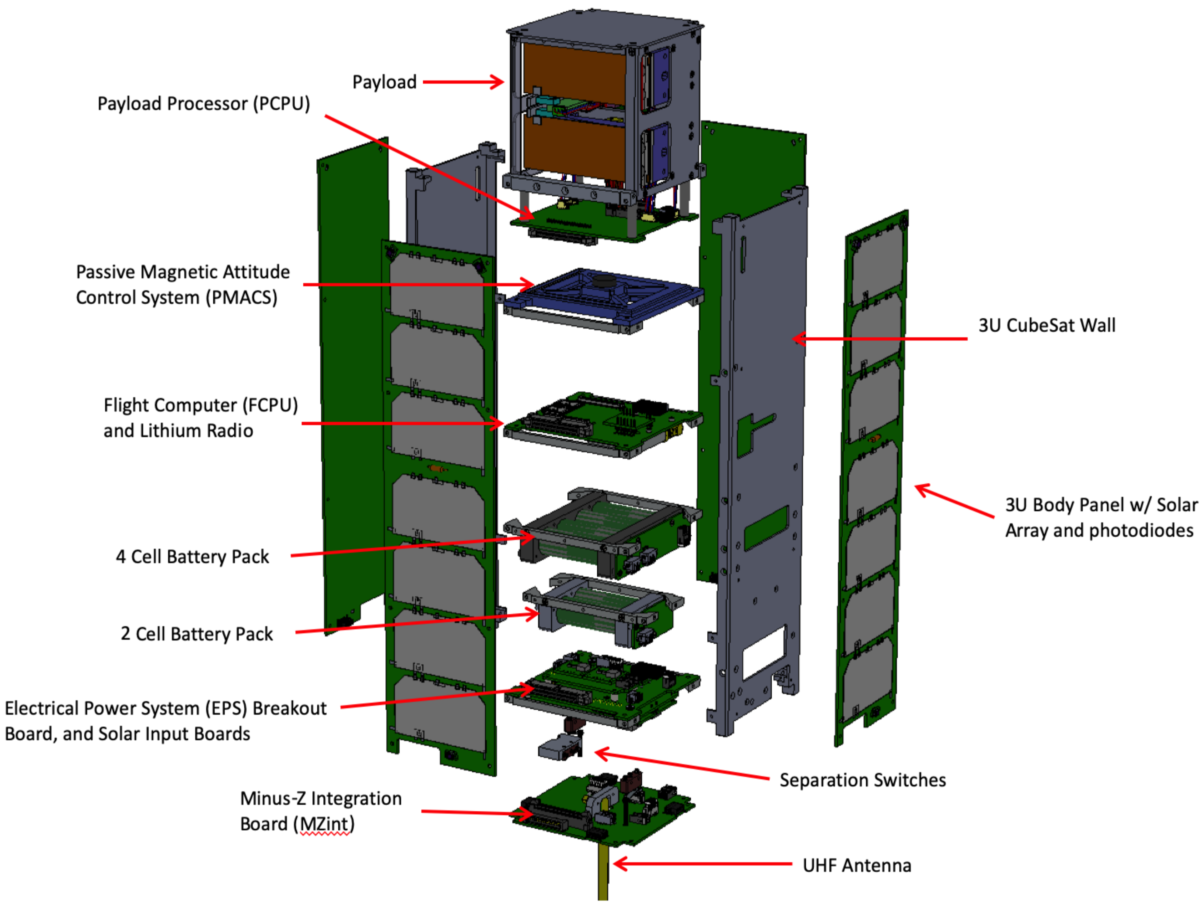
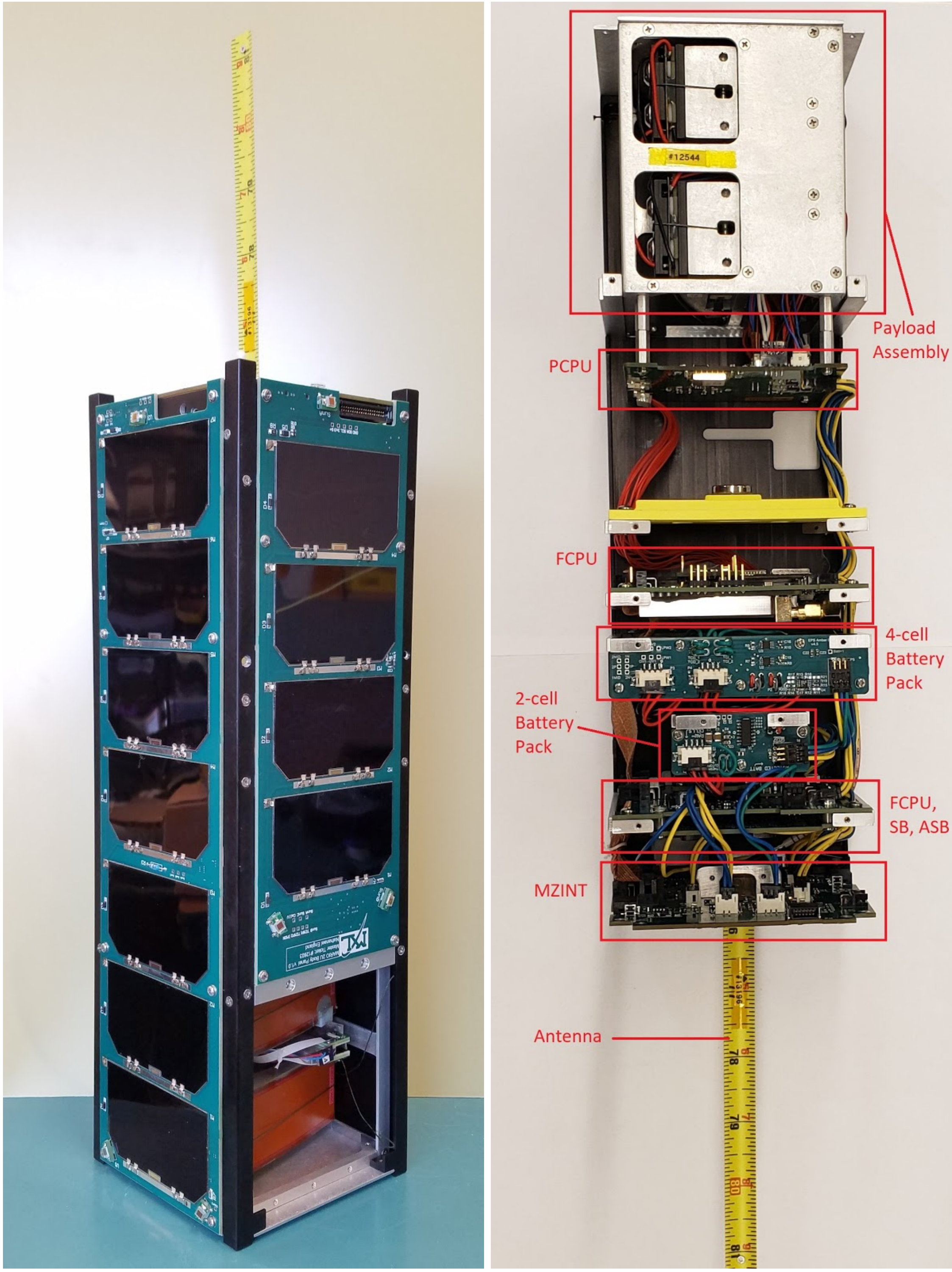


Fig 6. Engineering drawing of MARIO, exploded view with subsystems labeled.

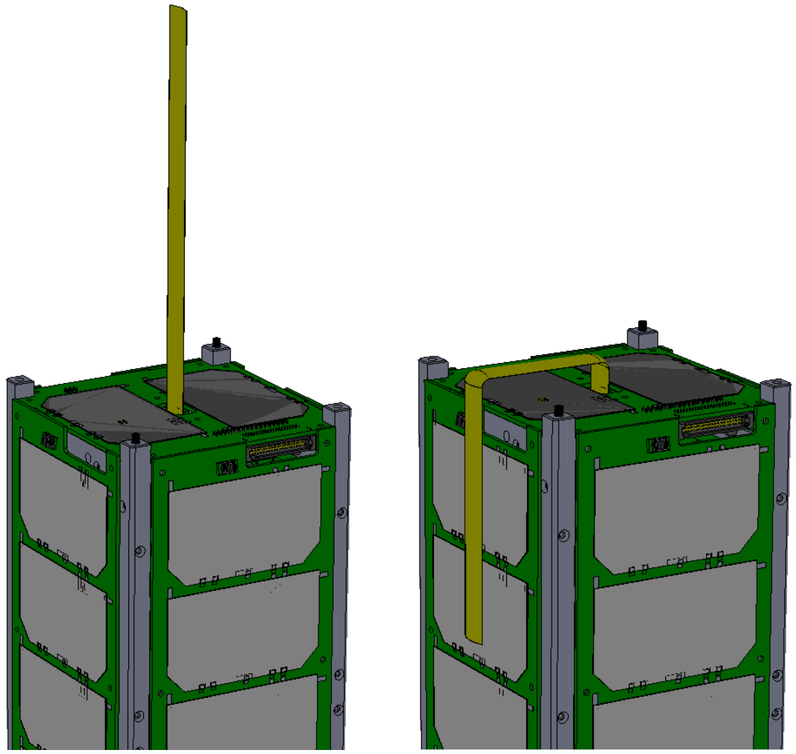
[8] https://www.jpl.nasa.gov/cubesat/missions/marco.php

[9] Szczerba, et. Al, *Expanding the Capability of Satellite Operations using a Global Federated Ground Station Network*. AIAA/USU Annual Conference on Small Satellites, August 2020. URL: <https://digitalcommons.usu.edu/smallsat/2020/all2020/161/>



(a) **(b)**

Fig 7. Photographs of MARIO engineering unit with antenna deployed. (a) shows the integrated spacecraft. (b) shows the spacecraft with one wall removed and subsystems labeled.



(a) (b)

Fig 8. Engineering drawings of MARIO with antenna deployed (a) and stowed (b).

Development Team

MARIO has been jointly developed by two laboratories at the University of Michigan for Extreme Diagnostics under NASA SBIR Contract 80NSSC20C0167, with advisement from the Jet Propulsion Laboratory at the California Institute of Technology. At the University of Michigan, the MARIO spacecraft is being developed by Dr. James W. Cutler's Michigan eXploration Laboratory, and the payload is being co-developed by MXL and Dr. Daniel Inman's Adaptive Intelligent Multifunctional Structures lab. While in orbit, MARIO will be operated by MXL from their university facilities in Ann Arbor, Michigan.