Attitude Control System for the Mars Cube One Spacecraft

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Abstract—**CubeSats are small spacecraft based on a 10cm by 10cm by 10cm (1U) cube standard that have historically only been operated in Earth orbit. Mars Cube One (MarCO) is the first CubeSat mission developed for interplanetary operation. MarCO is a technology demonstration mission comprised of two identical, solar powered 6U satellites with several key goals, including that of providing a bent pipe telecom relay to Earth for NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission during its Entry, Descent, and Landing sequence. MarCO launched on the same rocket as InSight and makes use of the Deep Space Network for communications and ranging. It therefore has an attitude control system and propulsion system suitable for operating in several pointing modes, providing desaturations for reaction wheel momentum buildup, and thrusting to change the spacecraft trajectory. Because the spacecraft design is constrained to the CubeSat standards and because of the distances of the spacecraft from Earth and the Sun, the components used for attitude control and propulsion must meet tight size, mass, and power requirements. Autonomous modes of operation are also critical to ensure that the spacecraft can function safely with periods of several hours occurring between consecutive communication periods. A robust testing sequence was required to ensure that the spacecraft functions were exercised and that the operations team understood how the spacecraft were expected to behave after launch. This paper discusses several elements of the MarCO attitude control and propulsion systems. The paper begins with a discussion of the hardware that was selected for the two systems as well as descriptions of the interface between the attitude control and propulsion systems and the interface between these systems and the rest of the spacecraft's command and data handling system. Next, the paper summarizes the different types of tests that were performed at the system and spacecraft levels. Test data is included for some of these tests which helped define the methods by which the spacecraft is operated in space. Lastly, the paper lists a series of lessons-learned for developing attitude control and propulsion systems for interplanetary CubeSats.**

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1. INTRODUCTION

CubeSats are small spacecraft based on a 1U standard, with each unit (U) defined as 10cm x 10cm by 10cm.[1] These spacecraft are often built using commercial-off-the-shelf (COTS) components to reduce cost and to enable development processes focused on subsystem integration rather than subsystem development to allow rapid design and build phases. CubeSats have been launched extensively to low earth orbit (LEO) over the last fifteen years. While missions to LEO are now commonplace, CubeSats have not ventured into deep space with the increased demands of communication over such long distances and propulsion for trajectory correction maneuvers.[2] Several spacecraft are being developed for future operations in such environments, emphasizing the need to demonstrate the key technologies prior to widespread adoption on other spacecraft.

The Mars Cube One (MarCO) spacecraft are a pair of 6U CubeSats designed to perform key technology demonstrations for deep space missions.[3][4] The primary components of each spacecraft are shown in Figure 1, and the fully assembled spacecraft are shown prior to integration with the launch vehicle in Figure 2. A launch vehicle-imposed 14 kg maximum mass allocation for each 6U spacecraft played a key role in the MarCO design. Launched with the NASA Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) lander in May, 2018, the MarCO spacecraft will serve as a bent pipe communications relay station during the InSight entry, descent, and landing (EDL) sequence in November, 2018. After the Mars flyby the MarCO Primary Mission will be complete, leaving the spacecraft in heliocentric orbit.

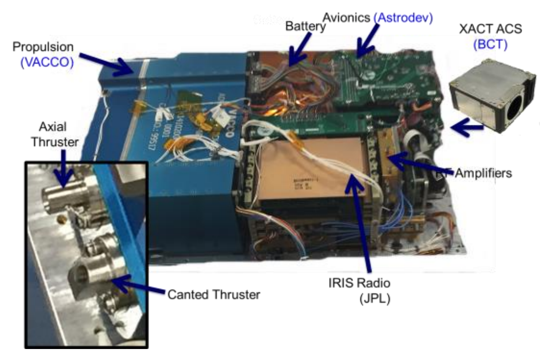

Figure 1. Internal Components of MarCO

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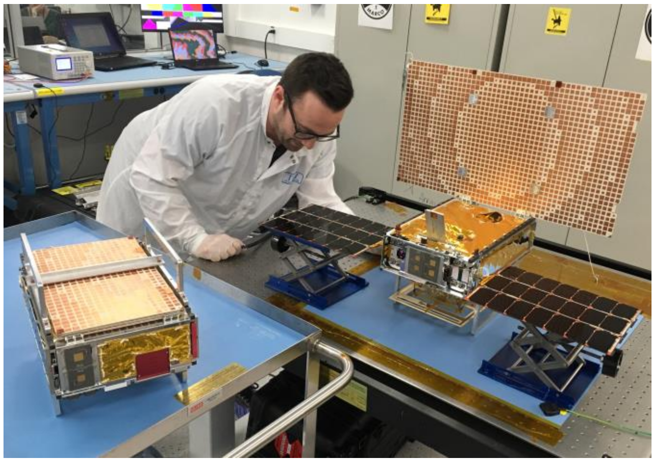

Figure 2. MarCO Spacecraft

While the twin MarCO spacecraft were designed with support of InSight EDL in mind, the primary purpose is to demonstrate the enabling technologies which ultimately make 1) future deep space CubeSats viable, and 2) future applications of the “bring your own relay” architecture viable. Future missions that bring their own small communications relay satellites for more permanent relay capability than MarCO will need to accommodate larger propellant tanks for orbit insertion. They will build on the basic functionality that has been demonstrated with MarCO. The overall mission plan is shown in Figure 3.

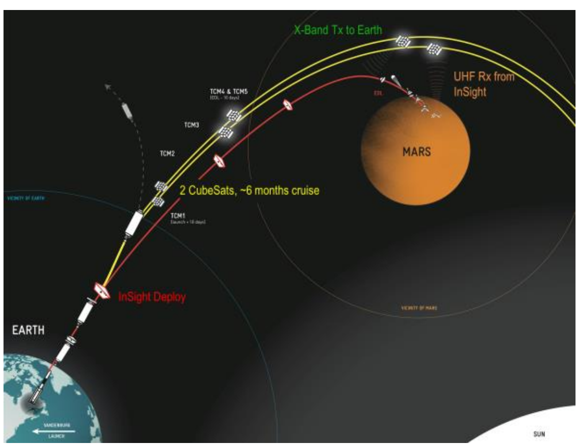

Figure 3. MarCO Mission Plan

The MarCO technology development objectives supporting EDL consist of a) demonstration of a planetary protection approach as applied to a CubeSat-sized spacecraft on a Mars flyby trajectory, b) deployment and inflight characterization of a flat-panel reflect array high gain X-band antenna c) deployment and inflight demonstration of a UHF loop antenna, d) demonstration of viable CubeSat operations at ~1.4 AU (such as the power, thermal, communication, and attitude control subsystems), and e) demonstration of the trajectory correction maneuvers required to execute a close Mars flyby in support of InSight’s EDL.

The enabling technologies for the latter two technology demonstrations are the focus of this paper. This paper presents the attitude control subsystem, which is based on the Blue Canyon Technologies (BCT) XACT integrated attitude control unit and Vacuum and Air Components Company of America (VACCO) Industries propulsion system.[5][6] The attitude control subsystem is critical for the success of the MarCO mission because of the need to ensure pointing the solar panels to the sun, balancing momentum buildup from solar radiation pressure and other disturbances, and fine pointing of the antennas to Earth and InSight.

The paper begins with an overview of the MarCO primary components before detailing the key interfaces between the XACT and the VACCO propulsion system. The process behind commanding both pointing thrusting events is described in the context of the COTS hardware that is used to perform each function. Additionally, system information is provided as a reference for future missions. The paper then discusses the verification and validation testing that was performed on the XACT system prior to launch, with test data included to demonstrate the ground performance of the system. Flight data is also presented to describe common flight operations. The paper concludes with a set of lessons-learned for developing deep space CubeSat attitude control and propulsion systems.

2. Attitude Control System Architecture

Architecture Overview

The attitude control system is comprised of the Blue Canyon Technologies XACT unit and the cold gas propulsion system by VACCO. MarCO’s XACT is configured with three orthogonally-mounted 15 mNms reaction wheels, an inertial measurement unit (IMU) with gyroscope measurements about all three axes, two coarse sun sensors (each with four photodiodes to provide approximately hemispherical fields of view), and a stellar reference unit (SRU). Therefore, while the attitude control and propulsion systems are largely COTS, the IRIS radio, interface boards, all antennas, and the deployable burn wires were not. The attitude control and propulsion systems consequently had a unique set of interfaces between each other and the rest of the spacecraft.

Each component has its own coordinate frame relative to the spacecraft body; this body reference frame is shown in Figure 4. Each reaction wheel rotates about a body axis. Similarly, the IMU measurement axes are reported in the body frame. The two coarse sun sensors are mounted on the +Y axis (so that they are aligned with the solar panel normal vector) and the +Z axis. Figure 5 and Figure 6 show the mounting positions for the two sun sensors, as well as the numbering scheme for their diodes. Lastly, the XACT’s SRU is mounted such that the SRU’s optics point out the spacecraft –Z axis, with the SRU boresight is canted 10 deg towards the spacecraft +Y axis.

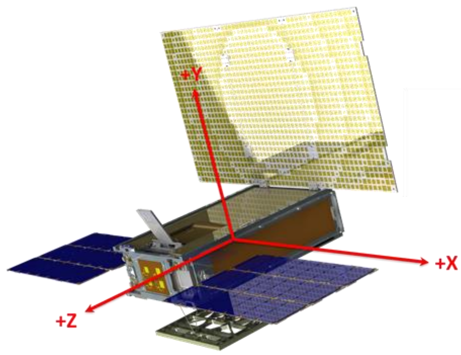

Figure 4. MarCO Body Coordinate Frame

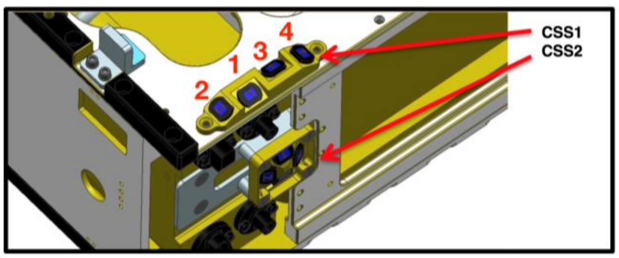

Figure 5. MarCO Sun Sensor Naming (Black) and CSS1 Diode Numbering (Red)

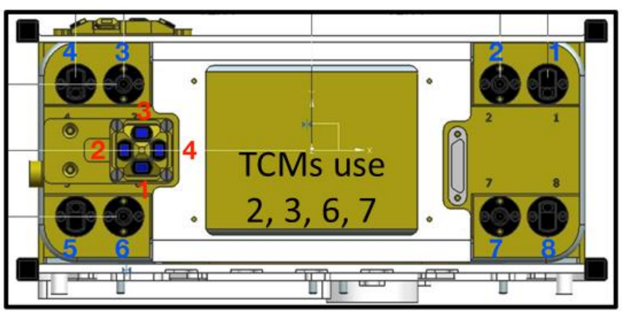

Figure 6. MarCO CSS2 Diode Numbering (Red) and Thruster Valve Numbering (Blue)

While the reaction wheels provide the primary spacecraft steering during the mission, momentum dumping and trajectory correction maneuvers (TCMs) are provided by a set of eight cold gas thrusters. All of the thrusters are mounted on the +Z face of the spacecraft. While all of the thrusters provide 25 mN of thrust at approximately an Isp of 40 sec, four have +Z-axis-oriented nozzles for trajectory correction maneuvers, and four have 30-degree canted nozzles for momentum desaturation. The momentum control thrusters therefore comprise the reaction control system (RCS). The four RCS thrusters can fire in pairs to provide torques about any of the three axes. Figure 6 shows the thruster numbering scheme.

The tank-to-plenum valve and the eight thruster valves are the only actuators in the thruster system. A block diagram showing the propulsion system components in Figure 7.

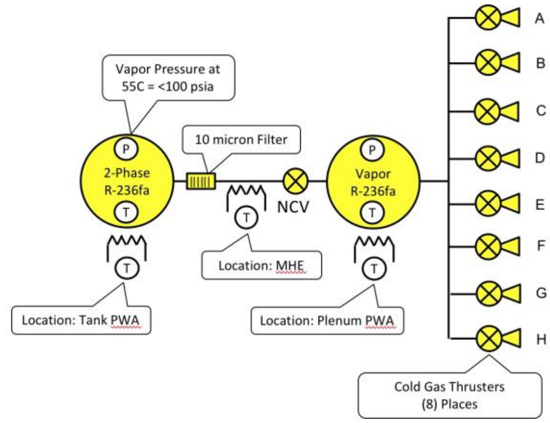

Figure 7. Thruster System Block Diagram

A defining feature for the thruster system is that all of the VACCO electronics are contained within the tank so that the propellant, R326fa, can be warmed without significant additional heater use whenever the thruster system is powered on. The internal diagram of the tank is shown in Figure 8.

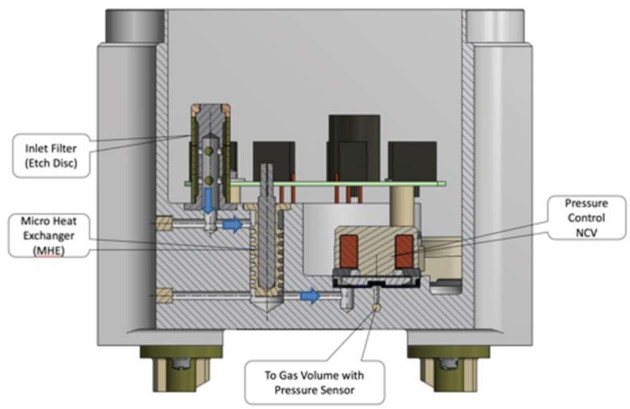

Figure 8. Thruster System Internal Diagram

The tank itself is an all-welded aluminum vessel, and there are five settable thermal control zones: the tank, plenum, manifold, and a pair of heat exchangers. The plenum is intended to contain strictly vapor propellant.

Propulsion System Budgets

The VACCO tank is sized to provide 40 m/s of DeltaV for the MarCO spacecraft. This amount of fuel corresponds to approximately 1.9 kg of R236fa propellant. The majority of the propellant is allocated for trajectory correction maneuvers, with up to five such maneuvers planned to ensure that the two MarCO spacecraft reach the desired target locations for relaying InSight EDL data back to Earth. Detumbling after initial separation from the upper stage rocket body was performed with reaction wheels only. Propellant had been allocated for assistance, however, and the vehicles could have autonomously made use of this propellant if necessary. This separate allocation of initial detumbling fuel mass was allocated because of the potential for high ejection tipoff rates of up to 10 deg/s per axis. The DeltaV and propellant budgets are listed in Table 1 and Table 2, respectively.

Table 1. Delta V Budget [m/s]

	TCM1	TCM2	TCM3	TCM4	TCM5	Total
Worst-Case Estimate	22.70	8.40	2.40	0.42	0.11	
					Sum	34.03
					Systems Margin	5.97
					Total Capacity	40.00

Table 2. Propellant Budget

Disturbance Torques	Propellant Mass [g]
Momentum Management	150
Detumbling	50
Reaction Control Margin	100
Reaction Control Total	300
Delta-V Propellant Need	1200
Delta-V Margin	370
Unusable Propellant	30
Total Propellant	1900

Pointing the Spacecraft with the XACT

For attitude control, the MarCO relies on two modes: sun point (sun-centered 2-axis mode) and fine reference point (3-axis stabilized mode). The controllers developed by BCT take command inputs that are defined in the body frame or in the inertial frame. The execution of attitude control changes and other attitude control and propulsion functions are handled by the XACT subsystem via high-level mode change commands. Low-level commands to individual actuators are then computed by the XACT's onboard software algorithms.

Operationally, the vehicles are autonomously configured to operate in sun point mode with a slow rotisserie of approximately 0.1 to 0.3 deg/s about the sunline to balance solar radiation pressure momentum buildup when not executing a communications pass. The sun pointing mode relies on the two sun sensors to locate the sun. Finding the sun is first performed with a full-sky search pattern. Once a sun sensor sees the sun, the spacecraft orients itself so that the +Y axis sun sensor is approximately orthogonal to the sun to illuminate the solar panels. The XACT may then be commanded to a rotisserie roll about the sun line. The roll about the sunline will include an IMU drift of approximately 10 deg/hr as determined from ground testing. Fine reference point mode uses the SRU to provide measurements to enable three-axis closed-loop control of the spacecraft, as well as to identify and correct IMU bias and drift.

Fine reference pointing commands for MarCO are sent to the XACT through the definition of primary and secondary command and reference directions. This approach, part of the BCT standard command set, allows MarCO to define attitudes relative to either the inertial frame or relative to celestial objects (such as the sun or geocentric nadir) and body vectors (such as the solar panel normal or an antenna boresight). Operationally, onboard storage of these parameters allows for the vehicles to provide the ACS subsystem autonomously with a target either by way of these high level constraints, or, if the situation warrants, with an exact attitude. One caveat to this approach is that it does not directly prescribe a specific trajectory between two attitudes; the slew path is selected autonomously by the XACT's onboard algorithms.

To support the attitude control architecture described above, the XACT contains several attitude vectors that can be selected as the primary or secondary command directions (the primary or secondary pointing constraints). The mission's critical attitude vectors are shown in Table 3. Most of the key hardware pieces are aligned with body axes, with each vector in the table indicating the unit vector for the X, Y, and Z body axes, respectively. The high gain reflect-array and medium gain patch antenna are co-boresighted and angled by 22.7 deg, however. This angle, and the UHF antenna boresight along the body –Y axis, are required for the relay of InSight's communication during EDL. The wide angle camera is angled to provide a view of both the high gain antenna and its feed in order to verify the deployment of each.

Table 3. MarCO Critical Attitude Body Vectors

Name	Vector	Use
TCM Delta-V Thrust Direction	[0, 0, -1]	Trajectory correction
Radiator Normal	[0, -1, 0]	Thermal management
Star Tracker Boresight	[0, sin(10º), -cos(10º)]	Attitude determination, 10°x12° FOV
Solar Array Normal	[0, 1, 0]	Power generation, thermal management
High Gain Antenna Boresight	[0, sin(22.7º), cos(22.7º)]	High-rate communications with the DSN
Medium Gain Antenna Boresight	[0, sin(22.7º), cos(22.7º)]	Medium-rate communications with the DSN
Low Gain Antenna Boresight	[0,0,-1]	Low-rate communications with the DSN
UHF Antenna Boresight	[0, -1, 0]	UHF relay

Narrow Angle Camera Boresight	[0, -1, 0]	Public relations, 3.4° half-angle FOV
Wide Angle Camera Boresight	[0, sin(62º), cos(62º)]	HGA deployment verification, 77° half-angle FOV

The deep space environment presents an increased radiation challenge for spacecraft compared to the LEO environment. The XACT is not susceptible to destructive latchup, though it is susceptible to occasional non-destructive effects. A power cycle is necessary to clear single event effects (SEE) to several devices within XACT and is used by system fault protection. Similar power cycling has been performed with the ASTERIA CubeSat, which includes an XACT of the same model. [7] An XACT power cycling is performed before critical maneuvers or when XACT telemetry shows non-physical values. The VACCO system is nominally powered off and only powered on for a thrusting event or check of its telemetry. Therefore, it routinely undergoes power cycling.

XACT to VACCO Interface

The XACT is connected to the VACCO system through a combined power and data cable. The interface between these systems as well as with the power and command and data handling (CDH) system is shown as a block diagram in Figure 9. The thrusters are operated over a 12V line, and the XACT sends commands to and receives telemetry from the propulsion board across a RS-422 serial interface. XACT can autonomously send commands to the thrusters in the event that a momentum dump is required to desaturate the reaction wheels as well as pass through ground commands.

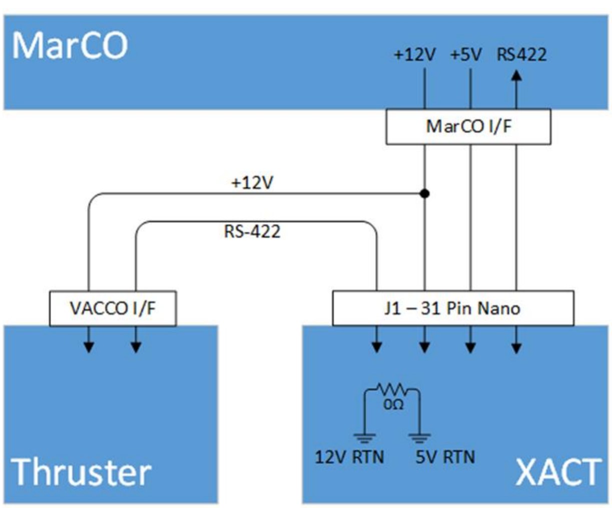

Figure 9. XACT-Thruster-CDH/Power Connections

Figure 10 shows the software architecture of the XACT, highlighting how commands to the propulsion system may be sent by a ground or CDH command (the Thruster Command block) or from XACT commanding (the Attitude Command block). The attitude control and propulsion hardware have dedicated controllers within the XACT as part of the overall XACT control loop, though propulsion-specific commands can bypass the attitude control block and directly control the thrusters.

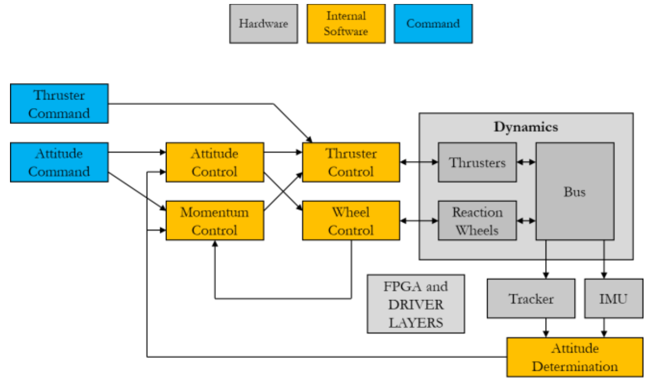

Figure 10. XACT Software Architecture

Actuating the Propulsion System

At a high level, management of the semi-autonomous XACT-VACCO system is achieved operationally by way of two parallel processes (implemented as command sequences). These processes monitor for nominal or off-nominal requests to pass commands to either the XACT or VACCO units. The first of these sequences, the Propulsion Manager, monitors the state of two wheel desaturation request flags: one can be raised autonomously (i.e. raised by the XACT) based on measured system momentum exceeding a threshold, and the other can be raised by a command from the ground. Upon observing one of these flags going high, the process powers on the propulsion system, applies heater and pressure set points, and when ready enables execution of thruster commands. The second of these, an ACS Manager sequence, sends the corresponding commands to XACT, and encompasses a larger set of simple ACS subroutines. This implementation method helps prevent multiple sequences from attempting to command the XACT at once (essentially serving as a single master), and also allows the ground to execute otherwise complicated sequences by stringing together multiple flag raises to the ACS Manager to execute different 'blocks' of reusable functionality. Consequently, the flexibility of operation affords the ability for the ACS Manager to serve the purposes of autonomous fault protection and nominal system state management.

Commands to fire thrusters for a TCM are sequenced by the operations team. These commands consist of a thrusting time and direction, dictated by the desired end-state of the firing. Attitude is maintained during TCMs by off-pulsing the thrusters due to the amount of torque required and uncertainties in spacecraft mass properties. The attitude controller for determining thruster firing times does not adapt to improve pointing performance over the course of a thrusting event, so the commanded attitude direction is specified using knowledge of how the spacecraft react to

TCM thruster firings. Because of the non-adaptive controller, the commanded firing direction makes use of known spacecraft thrusting response behaviors to compute an adapted firing direction that improves net thrusting performance. A software update to the XACT would be necessary to change the thruster controller gains and mass properties that are used for pointing during a burn.

At the end of the TCM, the spacecraft returns to fine reference pointing mode with reaction wheels controlling attitude to continue communicating with the ground station. TCMs have generally been performed during a period where the ground station is communicating with the spacecraft, though the slew to the firing attitude may result in dropped communication with the spacecraft.

3. Verification and Validation Testing

The hardware acceptance and integrated spacecraft testing at JPL of the attitude control and thruster capabilities for functionality and performance metrics as standalone units and as part of the overall flight system was primarily performed using a ground testbed.

Ground Testbed Description

The ground testbed, shown in Figure 11, is akin to a flat-sat version of the MarCO spacecraft, and it contains many of the same types of components as the flight models, though without the components being the actual flight components. For example, the separation switch circuit, command and data handling board, electronic power system board, main interface board, and battery are the same as those used in both MarCO spacecraft. Additionally, the XACT unit is nearly the same as the flight units with three reaction wheels, the IMU, the star tracker and a single coarse sun sensor.

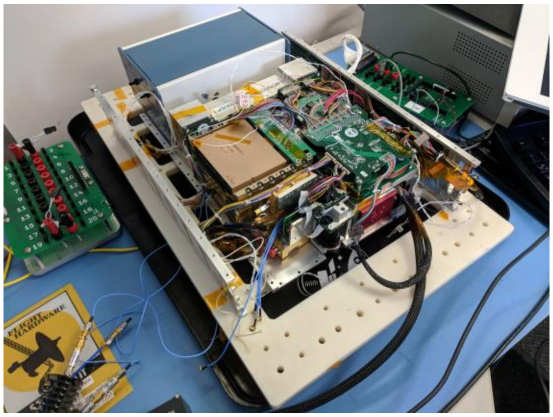

Figure 11. MarCO Testbed

The simulation environment for the XACT in the testbed is the Realtime Dynamics Processor (RDP) that was supplied by the vendor. This RDP enables hardware in the loop testing by simulating the sensor inputs during testing based on the XACT unit's actuator commands as if the spacecraft were in space. Additionally, it allows ground testers to command and receive telemetry through a test connector from the XACT at rates higher than flight rates for increased visibility into the XACT's performance.

The propulsion test unit consists of a vendor-provided electronics front-end that simulates the sensor readings and requires the appropriate heater loads for maintaining tank and plenum pressures. The connections are the same as on the flight unit, but propulsion hardware is not represented.

Ground Testing Process

In order to test the various functions of the attitude control system on the ground, an incremental and iterative process was followed similar to that described in [8], which enabled demonstration of the capabilities from basic functions to full flight mission scenarios. The determination of which tests needed to be performed was made based on the desire to perform the key mission milestones, standard daily operations, and fault recovery scenarios with flight-like access to commands and telemetry before launch. The testing was conducted primarily in the JPL CubeSat Development Lab (the location of the flight unit builds) as well as other lab spaces for several environmental tests, such as to use the Star Field Simulator from the JPL Small Satellite Dynamics Testbed [9] [10].

One of the simplest tasks that the XACT must perform is to point the spacecraft to the sun starting from an off-pointing stable attitude. Using the RDP to simulate the sun's position and the resulting sun sensor diode measurements, the XACT was shown to find the sun in less than a minute after being given the command to go to a sun pointing attitude for most initial attitudes. One such test case is shown in Figure 12.

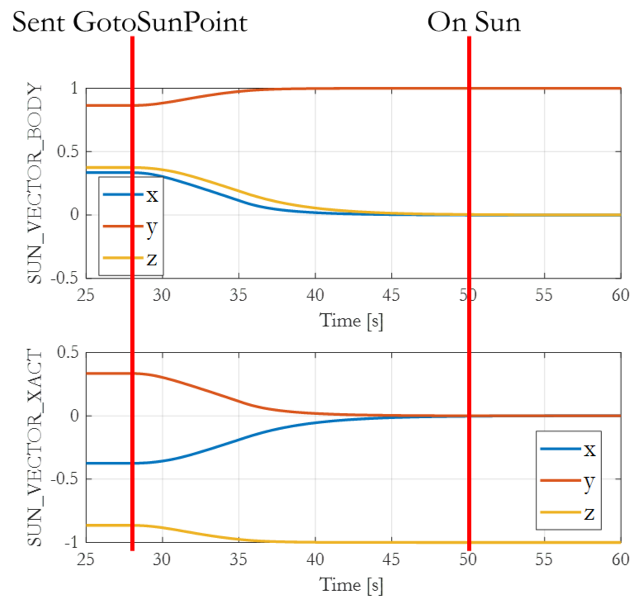

Figure 12. Testbed Test of XACT Achieving Sun Point Starting at a Stable Off-Sunpoint Attitude

A second test scenario is to start with a tumbling initial state and achieve a stable sun pointing attitude. The expected tipoff rate upon deployment from the launch vehicle for MarCO was < 2 deg/s. To demonstrate robustness, XACT was tested with an initial rate of 30 deg/s/axis as shown in Figure 13. This rate is higher than the reaction wheels' detumble capability, necessitating the use of thrusters to lower the system momentum. Immediately following the command to go to sun pointing mode, uses thrusters to counter the body rates autonomously. Thruster firing is indicated by the increase in thruster firing durations in the top two subplots and the effect is shown in the slowing of the body rotational frequency in the quaternion subplot. The system autonomously determines when the system momentum has been sufficiently reduced, ending the desaturation maneuver. The thruster firing durations do not drop to zero after they finish firing because the last value is stored and memory and returned throughout the rest of the test. The This test demonstrated the functionality of the interface and the control software between the XACT and VACCO units as well as the ability for the attitude control and reaction control systems to manage the spacecraft's overall system momentum and bring the spacecraft to a sun-centered state.

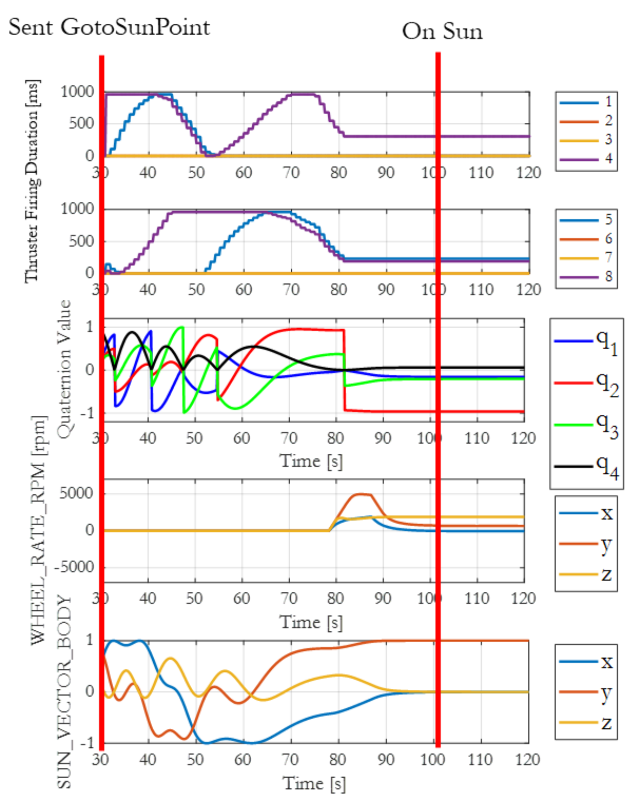

Figure 13. Testbed Test of XACT Achieving Sun Point Starting with 30 deg/s/axis Initial Tipoff Rate

Subsequent tests of the XACT and propulsion systems working in concert with the rest of the spacecraft were performed to emulate flight mission scenarios. These mission scenario tests included initial detumbling after deployment, sun pointing in safe mode, and performing the bent-pipe relay with InSight. Additionally, the mission scenario testing exercised the fault protection systems to ensure that the responses were well characterized and as expected. Since these tests are of the whole spacecraft as an integrated system, they provide the most realistic assessment of the spacecraft software's and hardware's readiness to perform the mission.

4. FLIGHT OPERATIONS

Flight operation of the two spacecraft occurs in a mission support area, or MSA. The MSA enables direct communication with the NASA Deep Space Network for sending commands to the spacecraft (one at a time) or receiving telemetry data from the spacecraft (either one at a time or from both simultaneously through multiple spacecraft per aperture, MSPA, configurations).

Initial Spacecraft Contact: A Demonstration of XACT Unit Capabilities

The initial contacts from MarCO came within two hours after separation from the launch vehicle. Data received showed that the spacecraft was powered on and able to point and communicate with the low gain antenna. This data provided the first assurance that spacecraft subsystems, including ACS, were functioning nominally. Figure 14 shows the reaction wheel speeds over the course of two five-minute long contact periods. The reaction wheels show near zero and constant rates, indicating a low overall system momentum and stable fine pointing.

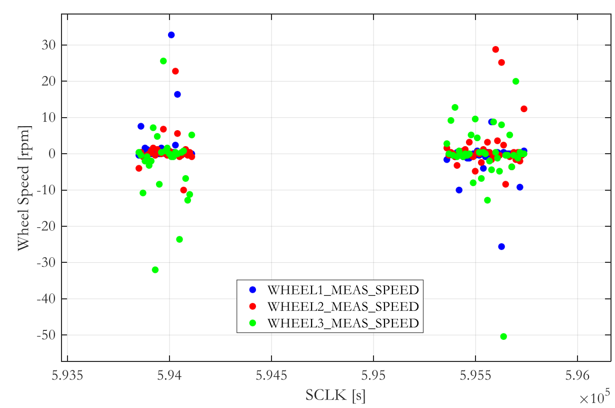

Figure 14. MarCO-A Reaction Wheel Speeds during Initial Post-Launch Contacts

Trajectory Correction Maneuvers: Demonstrating Propulsion System Capabilities

TCMs were implemented on MarCO as a series of short segments. Figure 15 through Figure 17 show data from the final segment of MarCO-A TCM-2. Figure 15 shows the increase in thruster accumulated burn times for this maneuver, with the upper plot showing the RCS thruster times while the lower plot shows the TCM thruster times. The reaction wheels are not used during TCMs, as indicated by the drop in the reaction wheel speeds during the thruster firing period to 0 rpm in Figure 16, with the transfer of wheel momentum into the body is counteracted by thruster off-pulsing during the spin down.

The resulting body rotation rates in Figure 17 show the effect of the thrusters starting to fire at approximately a spacecraft clock time of 505130 sec.

The spacecraft's center of mass is offset from the geometric center, and therefore the thrust generates non-zero rotation rates. For the first few seconds of the maneuver, axial thrusters 5 and 6 are off-pulsed more often than 1 and 2 to counteract this center-of-mass offset. After all 4 axial thrusters are firing, a net torque about the –Z axis was experienced, as evidenced by the firing of thrusters 0 and 4 for a longer duration at the start of the maneuver then thrusters 3 and 7 to counteract the torque. Additionally, there is a thrusting direction excursion primarily in the -X direction, as evident in the firing of thrusters 2 and 3 for longer than thrusters 5 and 6, during the first seconds of the TCM. These startup torques were consistently experienced on all TCMs on both spacecraft and are deemed to be due to imperfectly modeled spacecraft inertia, center of mass location, and thrust levels. The non-linear variations in the TCM thruster firing time curves shows the off-pulsing used to control the pointing of the spacecraft. At the end of the thrusting period, around 505156 sec, the thrusters cut off and control is given back to the reaction wheels. The large rotation rates after this time are a result of the reaction wheels moving the spacecraft back to the originally commanded attitude as a result of the thrusters imperfectly maintaining fine pointing during the thrusting maneuver. The final pointing error at the end of burn was approximately three degrees, which is a typical value experienced across all burn segments on both spacecraft.

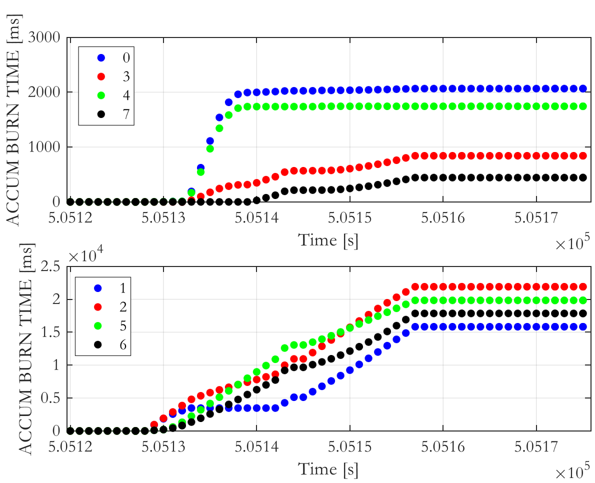

Figure 15. MarCO A TCM2 Cleanup Maneuver Thruster Accumulated Burn Times

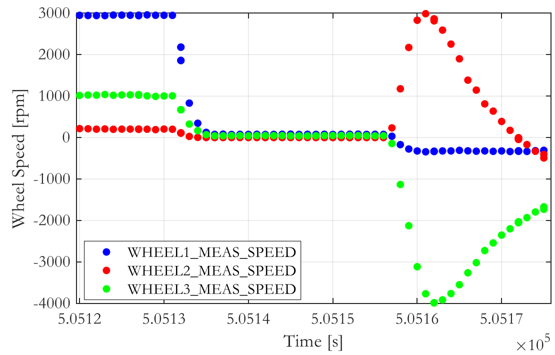

Figure 16. MarCO A TCM2 Cleanup Maneuver Reaction Wheel Speeds

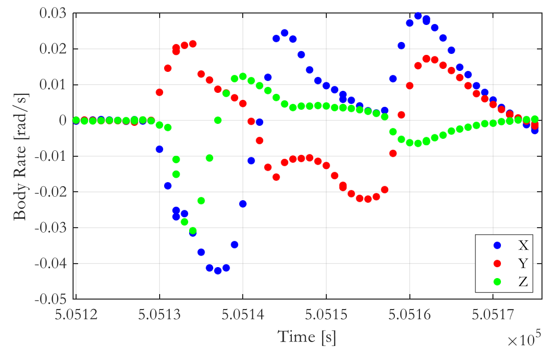

Figure 17. MarCO A TCM2 Cleanup Maneuver Body Rotation Rates

5. LESSONS LEARNED AND PAPER SUMMARY

The MarCO spacecraft development from initial concept though operation has provided several lessons learned for future deep space small satellite missions.

First, the testing phase demonstrated the usefulness of a parameterized set of fault protection parameters that govern the response of both the XACT and the CDH so that the values may be modified as necessary to accommodate different maneuvers in flight. Changing fault protection parameter for performing different maneuvers occurs only when the spacecraft is in communication with ground operators for the duration of the maneuvers. These same fault protection parameterizations also enabled the commanding of the spacecraft attitude and thruster firings with a reduced set of commands, making the process of operating each spacecraft less complicated and less likely to suffer command generation mistakes.

Further, the early operations and fault management periods demonstrated the usefulness of having the engineers who were deeply involved with the integration and testing of the spacecraft also serve as spacecraft operators. The intimate system knowledge of those who built and tested the spacecraft subsystems proved invaluable at determining the best course of action to respond quickly to limited data sets.

Additionally, the MarCO operations revealed a limitation of the XACT and VACCO interface in that autonomous momentum desaturation burns do not increment the accumulated thruster burn time telemetry values: a flight software update would be required to retrieve this information. The operations team uses these accumulated burn times as one method of determining how much propellant has been expelled over the course of the mission. Although each desaturation event does not require a large amount of propellant, it is difficult to determine the amount of fuel that is used. Tracking overall propellant use would therefore be improved if these burns had been incorporated into the total burn time telemetry.

The two-phase propellant system is not instrumented with direct measurements of neither propulsion volume remaining, nor propellent flow out of the tank. Rather, the plan was to track thruster usage duration and estimate the expected propellant usage. A leak in the valve between tank and plenum allows liquid to form in the plenum which, when a thruster is used, presents the potential to expel a combination of liquid and gas through the thruster. This phenomenon results in a poorly constrained relationship between thruster use duration and associated propellent mass loss, thus increasing uncertainty in the estimate of propellant remaining. Future missions could help improve their ability to diagnose, monitor, and recover from similar issues through a careful selection of instrumentation and telemetry for their specific propulsion and avionics systems.

In planning the TCM pointing directions, it was necessary to model the CG-offset and thruster force uncertainty-driven initial attitude excursion to compute a commanded thrusting attitude that would provide the desired TCM performance. The ability to have recorded gyroscope data to track the spacecraft's motion throughout each thruster firing event and the ability to have sufficient propellant onboard each spacecraft to conduct a thruster checkout program prior to the primary mission TCMs enabled the operations team to design thruster firings more accurately.

The operations team also gained experience with operating the SRU in multiple attitudes that include bright objects, such as the Earth and Sun, causing a loss of tracking lock. These short-duration losses of lock do not significantly affect the MarCO spacecraft's ability to maintain a valid estimate of its attitude, though an initially short duration loss may persist through the entirety of a slew if the commanded rate is sufficiently high or if the sun entered within an approximately 50 deg half-angle conical zone around the SRU boresight. As a result, some TCMs relied solely on the IMU for attitude propagation. Without the SRU's correction of the IMU's drift, the IMU-only TCMs remained within an acceptable error of approximately 3 deg for up to 70 seconds, motivating a segmenting of TCMs so that no segment would force the spacecraft to an undesired trajectory.

Additionally, the operations team developed methods for commanding the spacecraft to perform automated desaturation events based on varying system momentum trigger levels. It was determined that if an automated desaturation were to be commanded by the XACT when the reaction wheels were already spun down, then the spacecraft could perform a desaturation maneuver in the middle of an ongoing pointing-based process. Consequently, the team developed a sequenced version that can be performed autonomously for automated wheel desaturations that is triggered by a lower system momentum level than the XACT's level.

Conclusion

Both MarCO spacecraft are in the cruise phase to Mars and are performing well after an extensive integration and testing period. The spacecraft have successfully demonstrated their primary mission technologies, including the ability to perform trajectory correction maneuvers for deep space operations. The attitude control system and propulsion systems, comprised of COTS BCT and VACCO components, had been tested independently and together as a system in the lab environment prior to operation after launch. The ground testing validated the software and hardware interfaces, while also providing insights into subsequent operations. MarCO has comparatively loose pointing requirements, with communications being the primary driver, and the Martian environment is not expected to present attitude control or propulsion challenges to the spacecraft.

As the first interplanetary CubeSats, MarCO is demonstrating technologies necessary for subsequent missions and providing valuable guidelines and experiences for all phases of deep space small satellite missions as it completes the rest of its cruise to Mars to provide a bent-pipe relay for the InSight lander.

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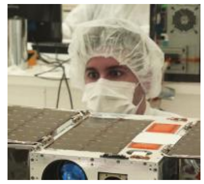

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