Mars Ascent Vehicle
Hybrid Propulsion Configuration

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As part of a Mars Sample Return (MSR) campaign, two Mars Ascent Vehicle (MAV) configurations have been designed in parallel. Each ascent vehicle configuration has a different propulsion system which ultimately leads to two unique vehicle designs. As part of a Preliminary Architecture Assessment (PAA), these vehicle designs were developed to the same level of maturity in order to inform the selection of one of the vehicles as the point of departure design for the campaign. The selection will be made in November 2019.

The initial MSR architecture called for a hybrid-based propulsion MAV. This type of propulsion system calls for a solid wax motor that would utilize liquid MON-25 as an oxidizer. Hybrid rocket propulsion allows for more flexibility than traditional solid or liquid propulsion options, and typically benefits from the advantages of both. A hybrid motor can be throttled and shut down easily, and avoids significant risk in manufacturing and handling. On a theoretical level, hybrid motors perform at a higher specific impulse (Isp) than solid motors. The primary disadvantage of hybrid motors comes from additional complexity and significantly less flight heritage and low Technology Readiness Level (TRL).

This paper describes the design of the hybrid propulsion configuration. An additional paper will be published describing the design of the solid propulsion configuration[1]. The hybrid propulsion configuration MAV was developed in 2019 by NASA Marshall Space Flight Center (MSFC) in association with NASA Jet Propulsion Laboratory (JPL). It features a Single Stage to Orbit (SSTO) design with an SP7A solid wax fuel and MON-25 liquid oxidizer. The liquid portion of the vehicle allows for a Liquid Injection Thrust Vector Controller (LITVC) as well as hypergolic propellant additives for ignition. The vehicle was designed to deliver approximately 0.31kg of Martian geological samples to a circular orbit at Mars of 343km at a 25º inclination.

Although hybrid propulsion in general has been used on launch vehicles in the past, the integrated vehicle subsystems that operate in conjunction with these propulsion elements do not typically operate in a Martian environment, which in this application can get as cold as -40ºC. The PAA advanced the maturity of these subsystems by performing detailed design and analysis on the vehicle with respect to structures and mechanisms, Guidance/Navigation/Control (GNC) systems, avionics, Reaction Control System (RCS), LITVC, thermal environments, and advanced Computational Fluid Dynamics (CFD). This paper will summarize the results of these studies.

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1. INTRODUCTION

The Mars Ascent Vehicle (MAV) concept is a significant component of the larger Mars Sample Return (MSR) campaign. The primary objective of this campaign is to return geological samples from the surface of Mars to Earth. Although a multitude of scientific robots and observation satellites currently exist on Mars, technological limitations prevent these platforms from truly duplicating an actual scientific laboratory that one could find on Earth.

The MSR campaign begins with the Mars 2020 rover, expected to launch from Earth in Summer 2020. Upon arriving on Mars, the M2020 rover will spend the next six years collecting samples of dirt, soil, rocks, and other deposits from the Jezero Crater on the Martian surface. The rover will package these samples in tubes and deposit them for collection at a later date. In 2026, MAV will launch from Earth, stowed upon a Sample Retrieval Lander (SRL). Upon arriving at Mars nine months later, the MAV will remain stowed while a Sample Fetch Rover (SFR) collects the deposited sample tubes. The SFR will then insert the sample tubes into the Orbiting Sample (OS), which is the payload for the MAV. After the SFR has completed delivery of 30 sample tubes to the MAV, the MAV will launch from the Martian surface. Upon achieving orbit, the MAV will eject the OS, which will then be captured by the Earth Return Orbiter (ERO) and returned to Earth.

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A hybrid-based propulsion architecture was originally proposed for MAV. Although at a lower Technology Readiness Level (TRL) than its solid configuration MAV counterpart, the hybrid configuration offers a number of advantages. A hybrid motor in general is a lot more versa tile, as it is capable of active shut down and throttling. This allows for active thrust correction and more accurate achievement of target orbit. Additionally, hybrid motors are theoretically able to achieve a higher Specific Impulse (Isp), effectively enabling it to deliver more payload. This configuration of hybrid motors also features a hypergolic ignition system, adding more flexibility to the mission. As with liquid engines, extremely cold environments such as one would expect on the Martian surface are expected to have a smaller effect on the performance of a hybrid motor. Finally, since a hybrid propulsion system features oxidizer and fuel in separate containment units, there are significant hazards avoided during ground operations prior to assembly and launch. As mentioned previously, the primary downside to hybrid propulsion is its relatively low TRL. Hybrid-based launch vehicles do not have nearly as much heritage in actual space applications as their solid and liquid counterparts. Some of the onboard components of the MAV configuration, such as a Liquid Injection Thrust Vector Control (LITVC) also feature a relatively low TRL. Additionally, introducing a liquid oxidizer adds complexity to the overall system, as a series of valves and pressurants are also needed.

A Preliminary Architecture Assessment (PAA) was completed to advance the fidelity of both a solid and hybrid configuration MAV to the same level of maturity. The hybrid configuration was designed to deliver 20 sample tubes to a circular orbit of 343km at 25º inclination around Mars. While doing so, it had to physically fit and remain operational within the SRL for the duration of the mission, while remaining within a specific mass constraint. The final design for the hybrid configuration MAV is shown below in Figure 1.

2. PRELIMINARY ARCHITECTURE ASSESSMENT

A PAA was completed to support the MSR campaign by maturing designs for two MAV concepts: a hybrid and a solid configuration, so that managers could make an informed decision on how to proceed with the mission. This paper will describe the hybrid configuration. In addition to technical design and analysis, the PAA existed to identify potential design issues for each configuration as well as programmatic design issues regardless of configuration. Ultimately, the PAA was the first actual design phase of the MAV.

The hybrid configuration vehicle began with an initial design phase. This involved an iterative process between GNC (Guidance, Navigation, and Control) and propulsion teams to design a motor that would deliver the vehicle to a target circular orbit of 343km along a 3DOF (Degree of Freedom) trajectory. Due to the active throttling and shutdown capability of hybrid motors, this was a fairly straightforward task, requiring few iterations. Following the 3DOF analysis, an initial CAD (Computer Aided Design) model was developed, which fed an aerodynamics and mass properties analysis. The results of these were then fed into a 6DOF analysis, ultimately leading to a final design featuring an active LITVC and RCS (Reaction Control System). Throughout this process, avionics and thermal subsystems were also assessed. Each of these subsystems provided

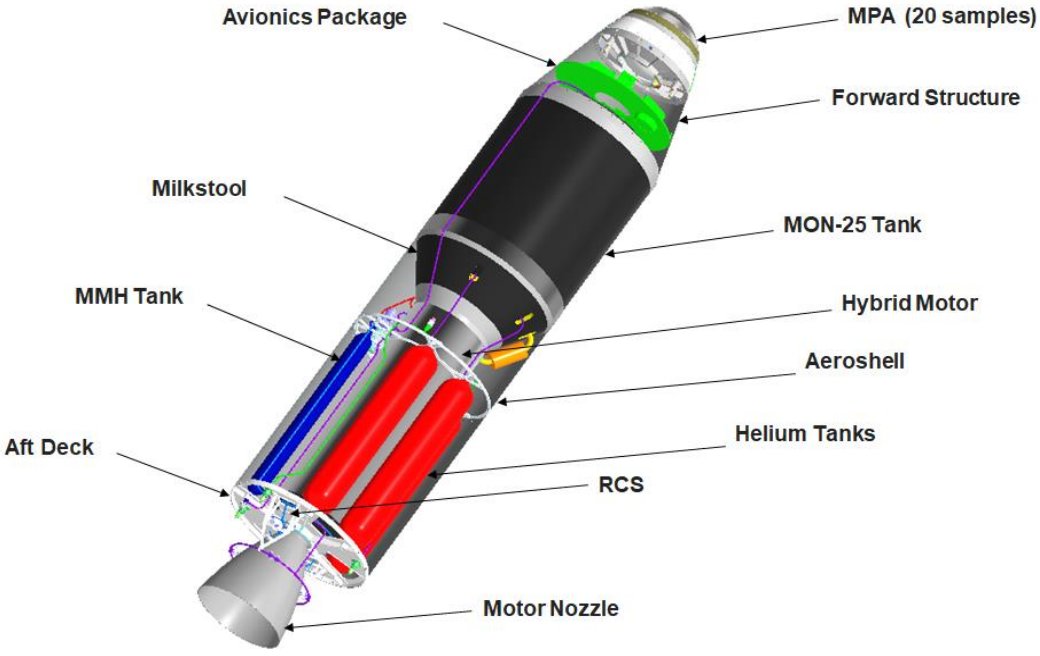


Figure 1. MAV-Hybrid Configuration Component Layout

estimated performance values that came into play with the driving requirements of the overall vehicle.

Although the PAA had a number of ground rules and assumptions associated with each of the individual subsystems, the driving guidelines behind the mission itself were comprised of three important factors: Orbit quality, physical size, and overall mass. A target orbit of 343km was desired, however, an absolute lower bound of 300km and a "soft" upper bound of 375km with a 25° inclination was needed to interface with the ERO. In addition, an eccentricity of less than 0.006 and a semi-major axis of ±9km was also within the design parameters. For physical size, a maximum length of 2.8m and a maximum diameter of 0.57m was needed to fit within the SRL. The target Gross Liftoff Mass (GLOM) was 400kg. The ultimate mission of the hybrid MAV configuration was to deliver a 14kg payload of 20 tubes of Martian sample to orbit.

3. THERMAL

The thermal environments encountered by the MAV were primarily broken up into two distinct configurations: a stowed configuration, which accounts for transit between Earth and Mars as well as Martian surface operations, and an operational configuration, in which it is actively exposed to the Martian atmosphere. While stowed aboard the SRL, the MAV is stored in a thermal enclosure known as the igloo. The igloo provides thermal insulation for the MAV as well as additional environmental protection from both deep space during transit and the Martian environment while on the surface. Figure 2 shows the MAV stored within the igloo inside the SRL.

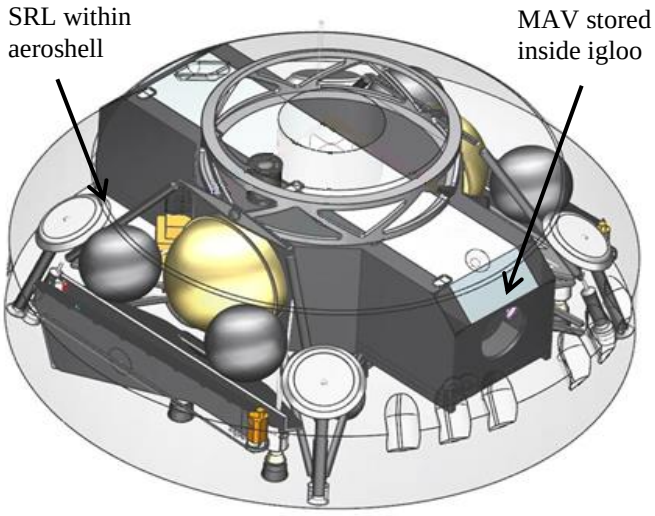


Figure 2. MAV Stowed on SRL

During transit, the thermal environment is driven by the SRL aeroshell temperature and optical properties. While stowed on the Martian surface, the thermal environment is driven by an expected outside temperature boundary of -62.5°C. High Technology Readiness Level (TRL) Thermal Control System (TCS) components are used to maintain MAV operating and non-operating temperatures during these times, as well as during all stages of flight. The primary TCS consists of a series of heaters/sensors, Multi-Layer Insulation (MLI), low emissivity tapes, CO2 gap insulation, and a traditional foam/cork Thermal Protection System (TPS). Although the outside temperature is expected to drop to a minimum of -62.5°C, this TCS is designed to maintain a non-operational Allowable Flight Temperature (AFT) aboard the MAV of -40°C and an operational AFT of -20°C.

The MAV TCS will utilize the same heaters to meet both operational and non-operational AFTS. Platinum Resistance Thermometers (PRTs) will be used to monitor the temperature of the MAV and provide feedback to the SRL for heater management. The vehicle will make use of 17 heater control zones, with each zone including a specific number of heaters controlled by an individual PRT. The basic layout of the heater zones are shown in Figure 3. Different heater sizes and shapes will be required to accommodate various components. Wherever possible, heaters will be wired in parallel to form a level of fault tolerance.

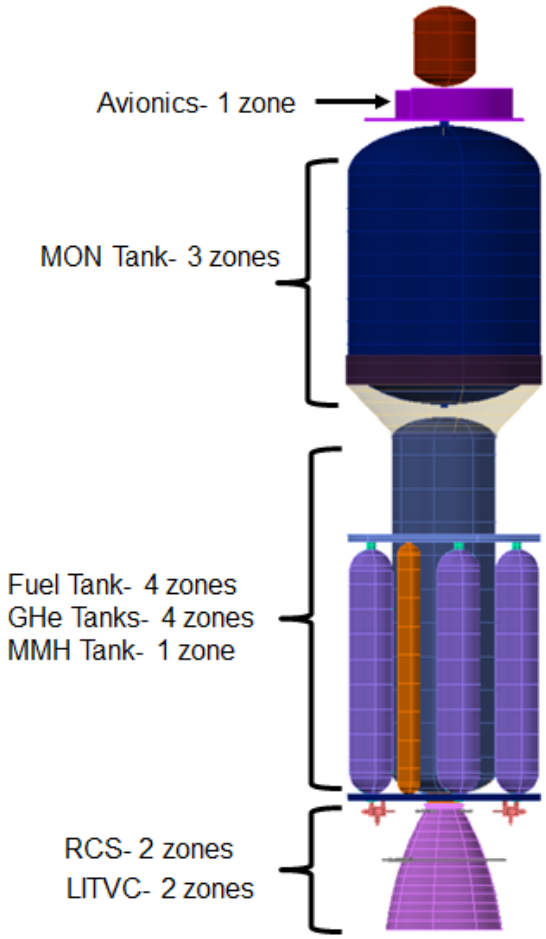


Figure 3. Heater Control Zones

In addition to heaters and sensors for temperature regulation, the MAV design features a number insulation materials. Although not yet in the actual MAV thermal design, MLI is reserved in the overall vehicle mass estimate. This insulation can possibly be used on the avionics to oxidizer tank interface. Blanket construction may include sheets of aluminized Kapton, Mylar, Dacron netting, Nomex threads, and polyimide tape. Low emissivity aluminized polyimide tape can be used to cover heater elements and on interior MAV surfaces. Materials such as these are at a high TRL and are currently used on the International Space Station (ISS), Hubble Space Telescope (HST), and Mars Exploration Rover.

The current vehicle design also features a traditional TPS. This system consists of a 0.5cm thick P50 cork covering the base region area to protect against base plume heating. A 0.5cm layer of Spray On Foam Insulation (SOFI) may also be used on the Outer Mold Line (OML) to protect from aeroheating as well as insulating some internal components. An ablative insulation material, Marshall Convergent Coating-1 (MCC-1) may be used on the aft end of the vehicle on components such as the RCS and LITVC, which may be subjected to base plume heating and nozzle radiation heating during launch and ascent. These TPS methods have been used on Delta IV, Space Shuttle, and Saturn V launch vehicles.

While stowed on the Martian surface, the volume between the igloo and MAV will be filled with CO2, which will act as an insulator by preventing natural convection. Insulation gaps of both 5cm and 10cm were examined for this study. A thermal analysis of the stowed vehicle within the igloo found that the TCS meets the MAV AFTs for transit to Mars, Martian surface operations, and Mars launch/ascent phases of the mission. To meet AFT constraints during Mars surface operations, the igloo 5cm CO2 gap configuration uses approximately 60% more power than the 10cm gap configuration. This applies to both operational and non-operational temperatures. An analysis of this power usage found that increasing the heater power during warmup from non-operational to operational temperatures can increase MAV internal component temperatures up to four times faster with a total energy decrease of up to 70%. A higher temperature gradient is not necessarily desirable, however, as some components, such the solid fuel component, may experience cracking if the rate of temperature change is too drastic. A solid fuel temperature gradient of 10°C/hr was desirable to minimize the risk of this grain cracking. Further thermal analysis found that both gap configuration did not exceed the allowable temperature gradient constraint. Ultimately, peak power from the thermal system during warmup was found to be 288W at a voltage of 36VDC.

4. AVIONICS

The MAV avionics system has three primary functions: maintaining command and data handling, communication, and providing power during flight. When possible, high TRL components were used, although a number of custom hardware elements were necessary. The primary hardware components used in the avionics design were an IMU (Inertial Measurement Unit), star tracker, radio transceiver, batteries, power distribution board, input/output board, and flight computer. The layout of the avionics hardware is shown in Figure 4.

Command and data handling is primarily carried out by the flight computer, star tracker, and IMU. These hardware components allow the vehicle to determine its attitude and positional data during flight. They also ensure the correct execution of custom GN&C algorithms through custom flight software.

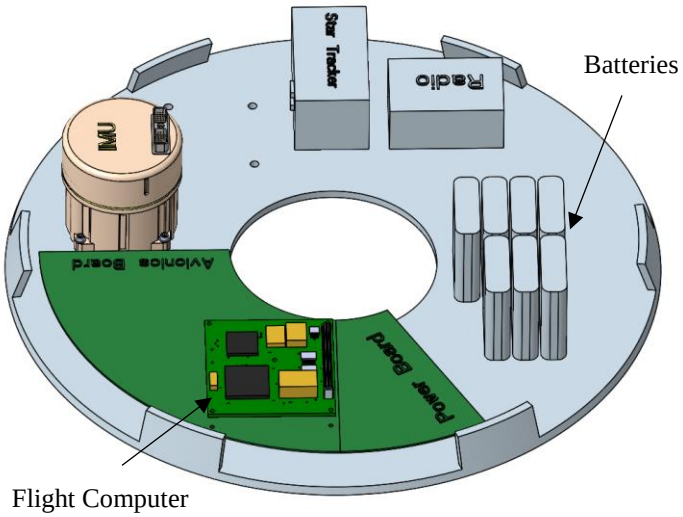


Figure 4. Avionics Hardware Layout

Communications are managed by the transceiver, antenna, and navigational beacon. All communication is with the Mars Relay Network (MRN), which is capable of returning data to Earth. Although the transceiver and antenna are important for broadcasting position and trajectory data, the sole purpose of the beacon is for the ERO to locate and capture the OS. Note that the beacon is not included in the avionics hardware, as its location within the vehicle is still to be determined. A custom distribution board is designed to administer power from an array of batteries to the individual avionics components. These batteries also provide power to the thermal heaters throughout the vehicle. A significant amount of cabling was needed to deliver power to these heaters. The beacon was powered independently. The overall avionics hardware architecture is shown in Figure 5.

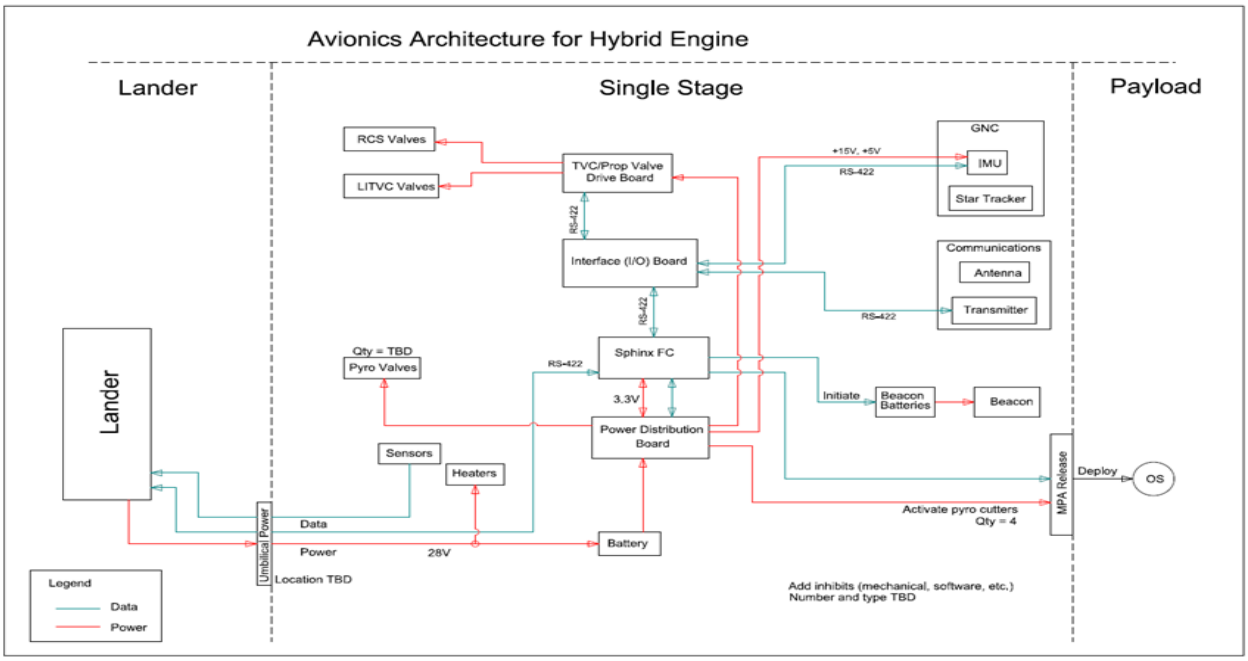


Figure 5. Avionics Hardware Layout

Prior to the actual start of the ascent portion of the MAV mission, a number of functions will be provided by the SRL. Attitude and position knowledge will be provided for state initialization and calibration of the IMU. Communications between the MAV and ground operations crew on Earth will be provided via umbilical connection. Fault protection will also be available to detect any off nominal conditions such as environmental or sensor effects found during regular health and safety checks. Additionally, the SRL will provide power to support battery charging and on board heaters. This will ensure that the MAV will only be under its own power for the ascent and orbital insertion portions of its mission.

A Sphinx flight computer was assumed for use as the primary computation component for command and data handling. This computer was developed by NASA JPL and selected based on its mass, power, and radiation tolerance. Although the actual flight software has not yet been developed, a customized version of the Core Flight System (cFS) framework will be used on the Real-Time Executive for Multiprocessor Systems (RTEMS) operating system.

The main software functionality will ensure that launch commit criteria are met, confirm launch once it has been commanded, interface with the IMU and star tracker to control RCS, valves, and LITVC, transmit navigation telemetry to the MRN, identify any error conditions, command/confirm stage separation, and command/confirm OS separation. The hybrid propulsion system presents additional challenges, as the flight software will be required to control propellant burn times actively during ascent and to optimize thrust termination times.

For position and navigational sensing, sensors similar to the Honeywell HG5700 IMU and Blue Canyon Technologies Nano Star Tracker (NST) were selected. The HG5700 capability was selected due to its small size with navigation-grade performance. This is necessary for achieving accurate attitude knowledge through gyrocompassing. An IMU such as this would still require qualification testing for space environments. Future studies will look at options to reduce vehicle performance requirements, which could potentially result in a smaller IMU. The star tracker can be used to augment the capability of the IMU for further performance. It was baselined for its size, weight, power requirements, and extensive flight heritage. The current GNC design plans to only use the star tracker after leaving the Martian atmosphere. The selection of these sensors are further detailed in Section 9.

The transmission of critical flight data such as flight phase and telemetry to the MRN was assumed to be provided by a transceiver similar to the ISIS TRXVU. Although this transceiver is capable of both sending and receiving communications, it was only used in this regard in a transmit functionality. The TRXVU was chosen due to its size, capability, and compatibility with the MRN. It will be used in conjunction with either an omnidirectional wraparound or patch antenna. The aforementioned beacon will also use this antenna to broadcast position data to the MRN for capture of the OS by the ERO. This beacon will remain operational on the spent MAV upper stage for up to 45 days following OS orbital injection.

While stowed prior to flight, power will be provided to the MAV by the SRL through an umbilical connection. During

flight, however, onboard power will be needed to power avionics components, TCS, and RCS/LITVC valves. This power will be provided by batteries similar to SAFT 176065 cells. These cells were selected for their ability to perform in cold temperatures, low loss during long storage periods, and recharge ability.

5. PROPULSION

The hybrid configuration MAV consists of a single stage hybrid motor, featuring a liquid MON-25 oxidizer and a solid wax based SP7A fuel. The motor burn rate is dependent on oxidizer mass flow, with a very weak dependency on pressure and temperature. The shear force from the oxizider creates an instability in the fuel, acting as a fuel injection system and increasing the burn rate over conventional hybrid fuels. The propulsion element itself is comprised of the actual liquid oxidizer tank, solid hybrid motor, helium pressurant/RCS tanks, a hypergolic ignition tank, and the nozzle. Additional structural elements are used to house these components. RCS thrusters and LITVC nozzles are also present for attitude control. The propulsion system layout is shown in Figure 6.

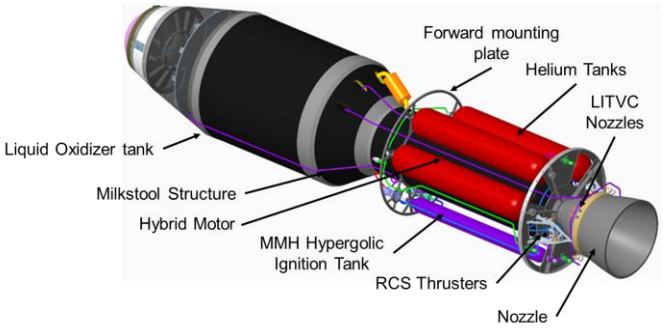


Figure 6. Hybrid Propulsion System Layout

Initial sizing of the vehicle components were driven by mass and physical size (length/diameter) constraints. MON-25 was selected as the oxidizer for this application due to its relatively low freezing point of -55ºC, which falls well below the design non-operational temperature of -40ºC. The SP7A solid fuel component is already known to withstand similar extremely low temperatures. The MON-25 tank was designed as a Composite Overwrap Pressure Vessel (COPV) with an aluminum liner, providing structural support for the vehicle as well as storage for the oxidizer. Although slosh analysis was not included in the PAA, slosh baffles were included in the MON-25 tank design to account for the additional mass. Future slosh analysis can potentially remove or reduce the number of slosh baffles. Additionally, an integrated baffle design could potentially cause tank deformation upon pressurization. The actual MON-25 tank is shown in Figure 7.

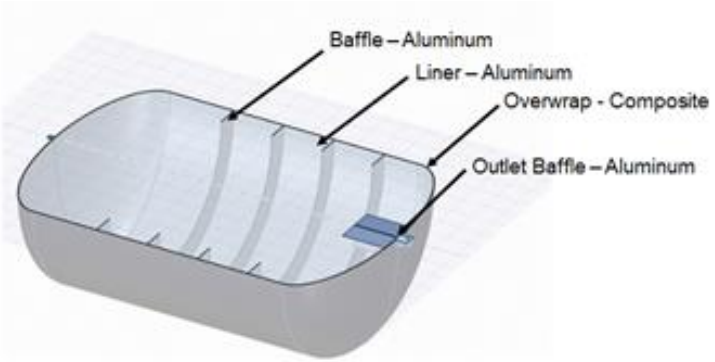


Figure 7. MON-25 Tank

The motor features a Hydroxyl-Terminated PolyButadiene (HTPB) forward and aft dome with the wax based sold SP7A fuel segments in between, forward of the actual motor nozzle and throat. In this configuration, the MON-25 oxidizer and hypergolic monomethylhydrazine (MMH) are injected into the HTPB forward dome for ignition. Figure 8 shows the layout of the hybrid motor.

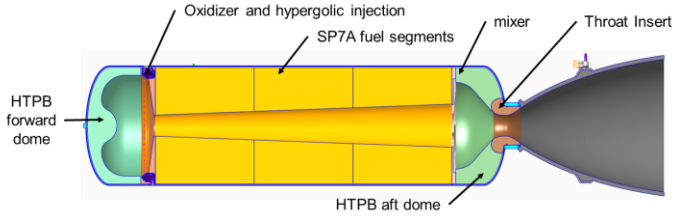


Figure 8. Hybrid Motor Layout

The hybrid propulsion system features a helium pressurant to inject oxidizer into the hybrid motor. A series of regulators control the actual oxidizer pressurization and flowrate. A high pressure regulator reduces the helium from tank pressure to a lower pressure, where a low pressure regulator further reduces it for operation. This helium is also used for RCS. The four helium tanks used for this surround the hybrid motor itself with a fifth tank used for MMH. Hypergolic ignition analysis and testing was completed to investigate the pre-ignition environment for the hybrid motor and ignition test article at Martian standard temperatures and pressures. Due to availability, a triethylaluminum-triethylborane (TEA/TEB) hypergolic ignitor was used during testing. The results of the analysis and tests showed that the MON-25 TEA/TEB reaction ignition delay was much larger than desired for this motor and test article, and that a sustained ignition would be unlikely in a Martian environment. A redesign of the injector chamber yielded a more favorable pre-ignition environment for stable ignition, however, repeating the test with actual MMH at standard Martian temperature and pressure is still needed to confirm its performance.

The motor nozzle is a fixed design that must survive two burns. Analysis and testing has demonstrated a higher than

desired throat erosion rate. This affects pressure and area ratio over the length of burn for the mission. A number of different nozzle materials are available, which may reduce nozzle erosion. Additional planned testing will further determine the capability of these materials. Operation of the LITVC will further affect nozzle design. Contrary to a traditional electromechanical actuator TVC design, the LITVC deflects flow at the injection points. LITVC, ignition, and burn tests are planned at various MAV partner organizations[2] in the near future.

The MAV hybrid motor performance was calculated using NASA's One Dimensional Equilibrium: Chemical Equilibrium Analysis (CEA) software with an assumed nozzle efficiency. CEA helps determine the most efficient rocket parameters. Following the initial motor design with CEA, a Two Dimensional Kinetics (TDK) nozzle analysis was performed. TDK analysis calculates nozzle boundary layer flow, two phase flow losses, and the amount of combustion gas that will react when in the nozzle. It will also theoretically give an optimal nozzle contour. When performed with MAV, TDK indicated that the assumed nozzle efficiency was too high, and that the best nozzle performance would actually be achieved at a lower mixture ratio. This ultimately results in a lower overall motor Isp due to an overestimated nozzle performance. The motor design will be updated in the next analysis cycle to account for an updated nozzle. An increase in mass is expected.

A Computational Fluid Dynamics (CFD) analysis was performed on the propulsion system to determine a number of induced environments. Acoustics, from both an internal chamber perspective and from a liftoff and plume-induced environment perspective were analyzed. Liftoff acoustic analysis found the liftoff environment to be benign compared to a similar terrestrial launch arrangement and that ultimately, acoustics during liftoff were not a concern. A similar conclusion was drawn from plume induced acoustic environment and ignition overpressure analyses. Thrust oscillation analysis found that peak thrust from ignition oscillation was not large relative to total thrust when stable.

The hybrid motor design meets performance constraints from a propulsion perspective, by delivering the payload to orbit while remaining within designed physical constraints. Due to its lower TRL, a number of tests will still need to be complete to demonstrate that the necessary Isp can be delivered. Additional analysis can be performed to further optimize mass. Although orbit quality will still need to be fully assessed with respect to dispersions, the capability of motor shut off adds flexibility to the design and allows for straightforward design modification in the future.

6. RCS

The MAV hybrid RCS consists of a regulated helium cold gas system containing high TRL components. As helium is already used as an oxidizer pressurant, it does not add additional mass or complexity when used for RCS. The MAV RCS consists of six independent thrusters to provide attitude control and two settling thrusters. The RCS provides only roll control during engine burn, with the LITVC providing pitch and yaw control during these ascent phases. During coast, roll, pitch, and yaw are provided by the RCS. Additionally, the RCS provides axial settling thrust prior to secondary burn. Figure 9 shows the location of the RCS thrusters with respect to the motor nozzle.

The RCS thrusters themselves were originally designed for liquid propellants. Current modifications are in work to adapt these for use with this specific application for helium. These can potentially be used for LITVC as well. The nozzles can be optimized to operate at temperatures as low as -60°C as a worst case. It is assumed that most RCS will be used at the beginning and end of the coast period to maintain accurate vehicle attitude.

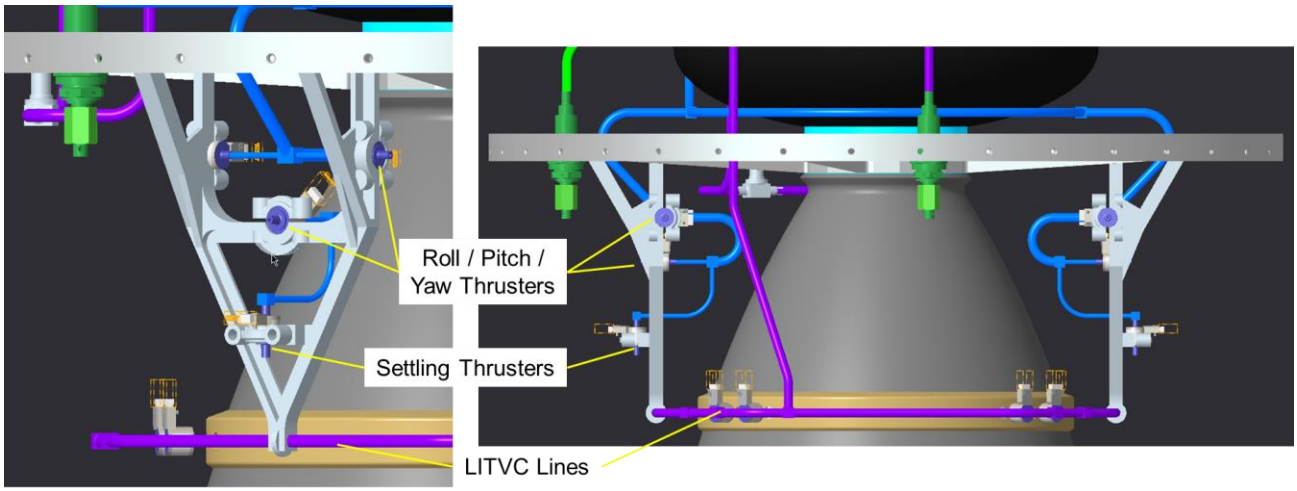


Figure 9. RCS and LITVC Components

Control of RCS is performed through the flight computer. A common controller drives valve coils for both RCS and LITVC. The controller and valves are powered through onboard vehicle batteries.

7. TVC

Contrary to a traditional electromechanical actuator TVC design, the LITVC deflects flow at specific injection points within the motor nozzle. This allows for pitch and yaw control without the additional complexity of external actuators. It shares oxidizer and pressurization tanks with the main motor, so it also does not require too much additional mass. It does have limited heritage, however, giving it a moderate TRL. To maximize LITVC effectiveness during launch and ascent, it was designed to have an equivalent of 5º thrust vector angle at the nozzle throat.

The LITVC valves are similar to the modified valves used for RCS. Each injection point features a dual valve port design. This doubles TVC effectivity at the cost of increased propellant consumption for brief periods of high demand, such as at launch or second burn ignition. It also adds a second layer of redundancy to each port. The LITVC valves are supplied oxidizer through a common manifold fed from the MON-25 tank, and supported by the same aft deck structure as the RCS. As with the RCS, LITVC valves are controlled through the flight computer and powered through onboard vehicle batteries.

8. STRUCTURES

A structural analysis was performed on the integrated vehicle to ensure that it would survive the loads environments encountered during its mission. A typical launch vehicle undergoes maximum load in an axial direction during ascent. MAV presents a unique situation, however, as it is expected to experience a maximum acceleration of approximately 15g in a lateral direction while stored on the SRL during Martian EDL. Additionally, the initial Center of Gravity (CG) of the vehicle plays an important role in this regard, as the overall balance and performance of the SRL is effected by MAV CG. MAV was structurally designed to have monocoque construction, therefore making its structural attach hardpoints to the SRL a significant point of design. Integration with SRL designers found that the attach hardpoints would be suitably located on the oxidizer tank and aft deck in the locations shown in Figure 10. Although the CG is cantilevered in this configuration, it is not significant enough to result in an undesirable structural response.

Although the EDL phase was the highest structural loads environment that was found, the analysis also assessed the vehicle response to Earth departure, parachute mortar firing, parachute snatch, and Mars touchdown loads. Integrated vehicle components such as the forward structure, milkstool, and aeroshell were examined. No stiffening elements were designed or included in the design. Assuming a reinforced composite fiber material on these allowed for the thickness of the components to be determined. This material thickness calculation took into account failure modes such as strength failure and buckling, and included a yield strength factor of safety of 1.25 as well as an ultimate strength factor of safety of 2.0. In addition to the aforementioned loads, an induced aeroacoustics loads environment was developed in order to to determine the effects of unsteady aerodynamics on the vehicle. This analysis found that the induced sound energy on the vehicle was encountered at a maximum by the midsection of the vehicle during ascent. Due to the relatively thin Martian atmosphere, this aeroacoustic environment can be compared to the sound energy generated by a jet aircraft engine from 50 feet away. Although this could be harmful to a human ear, no significant impact was found from the loads this generated on the vehicle itself. If the skin of the vehicle were to be decreased in thickness at some point in the future, it is possible that the aeroacoustics environment may pose a larger threat, especially to the components contained within the aeroshell. Although buffet loads were originally considered for the PAA, it was later determined that differences in buffet forcing functions between solid and hybrid configurations would be minimal, and therefore development of that analysis was deemed out of scope.

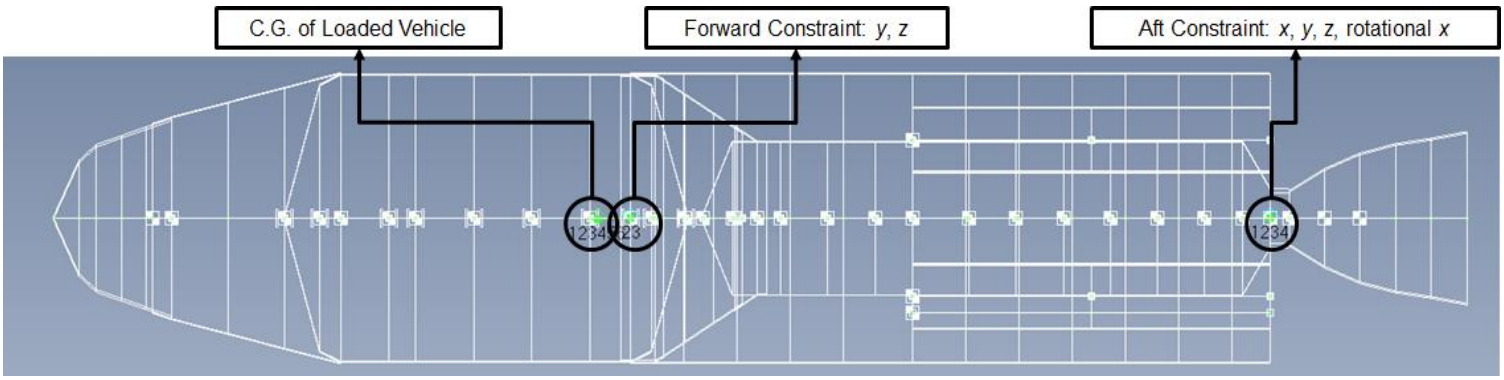


Figure 10. SRL Attach Points

9. GNC

The hybrid MAV configuration was designed to deliver a 14kg payload to a circular orbit of 343km at a 25º inclination. An iterative process was necessary to design and analyze a vehicle trajectory capable of completing this mission. Additionally, performance capability of the vehicle RCS and LITVC was assessed. In order to determine necessary vehicle parameters, a navigation sensor study was also completed.

Initial mission analysis for MAV featured design of a 3DOF trajectory. Although this type of trajectory only considered translational motion of a point mass, it was vital in determining how the overall vehicle payload mass would factor into the vehicle GLOM as well as overall capability of the two solid motors. Ultimately, the 3DOF trajectory determined the necessary vehicle thrust and propellant flow rates, which were used in sizing of various vehicle components. Following the design of the 3DOF trajectory, an updated Mass Equipment List (MEL) was generated from other vehicle subsystems and integrated with an aerodynamic database to design a 6DOF trajectory. This trajectory featured vehicle roll, pitch, and yaw rotational body rates in addition to translational motion. The 6DOF analysis was vital in determining how capable the LITVC and RCS needed to be, as well as evaluating how well mission design objectives were met.

The initial 6DOF trajectory design uncovered an attitude control issue post-Main Engine Cutoff (MECO). A high dynamic pressure was observed directly at MECO. Combined with large body rates and angles of attack, these orbital parameters contributed to an undesirable vehicle attitude motion. An RCS analysis found that thrusters would need to be extremely large to overcome these aerodynamic moments until the vehicle left the atmosphere. Contributing to this undesirable issue was an unavoidable control problem inherent in this hybrid propulsion vehicle design. As propellant is burned during flight, the CG moves further aft.

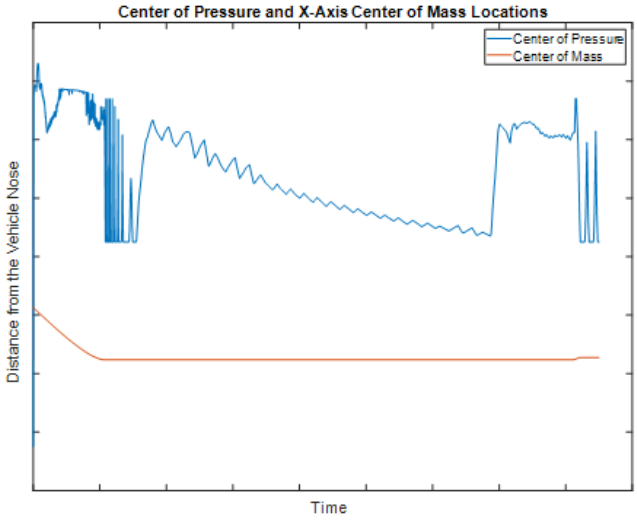


Figure 11. Aerodynamic Stability

This results in a smaller moment arm between the CG and RCS/LITVC application points, ultimately meaning lower control authority as the vehicle continues to fire its motor. As the CG already begins aft of the Center of Pressure (CP), the vehicle was found to become more statically unstable throughout flight, shown in Figure 11.

To mitigate the stability issues, a new 3DOF target trajectory was created. The goal of this design was to produce a MECO target for 6DOF which would reduce the dynamic pressure and angle of attack, while maximizing the payload to orbit. Ultimately, a lofted trajectory was created to meet these constraints, reducing the first burn duration to meet a desired dynamic pressure. The resulting nominal 6DOF trajectory did not have an instability issue at MECO. All original design metrics were also met with regard to GLOM, physical size, and orbit. The nominal flight plan is shown in Figure 12, featuring a burn to MECO, coast to apoapsis, and burn to circularize the orbit. Both burns feature closed-loop Powered Explicit Guidance (PEG). PEG uses predictor-corrector guidance to take advantage of the hybrid motor cutoff ability. Aero null guidance is used during the first burn to maintain MECO stability.

In addition to nominal trajectory analysis, a number of simulations with dispersed parameters were performed to determine their effect on the vehicle's performance. Launch conditions, atmosphere, payload mass knowledge, vehicle mass properties, and aerodynamic coefficients were varied to determine their effect on key orbit metrics such as altitude, inclination, and eccentricity. In the future, additional dispersions such as thrust misalignment and lateral CG would be desirable to investigate.

For launch condition dispersions, 225 individual cases were run. These cases specifically varied launch angle and azimuth. All 225 dispersed cases were found to fall within target orbit boxes. For modeling of the Martian atmosphere, the 6DOF model calls upon a lookup table built from the Mars Global Reference Atmosphere Model (MarsGRAM). To vary environmental conditions, two cases of solar flux and dust tau lookup tables were built. Both cases showed final orbits within the target boxes. A payload mass knowledge error dispersion was performed to address cases where the vehicle's predicted payload mass was not loaded onto the vehicle. This is especially applicable, as the density of the Martian samples collected will vary. The study found all cases to close within target orbit boxes.

Vehicle mass properties and aerodynamic coefficients were dispersed to assess their impact on RCS and LITVC consumption. Moments of inertia, axial CG, and both axial and lateral aerodynamic coefficients were varied. Control authority and stability issues were found in a number of dispersed runs at the end of MECO. Additionally, it was found that certain low off-nominal mass moments of inertia

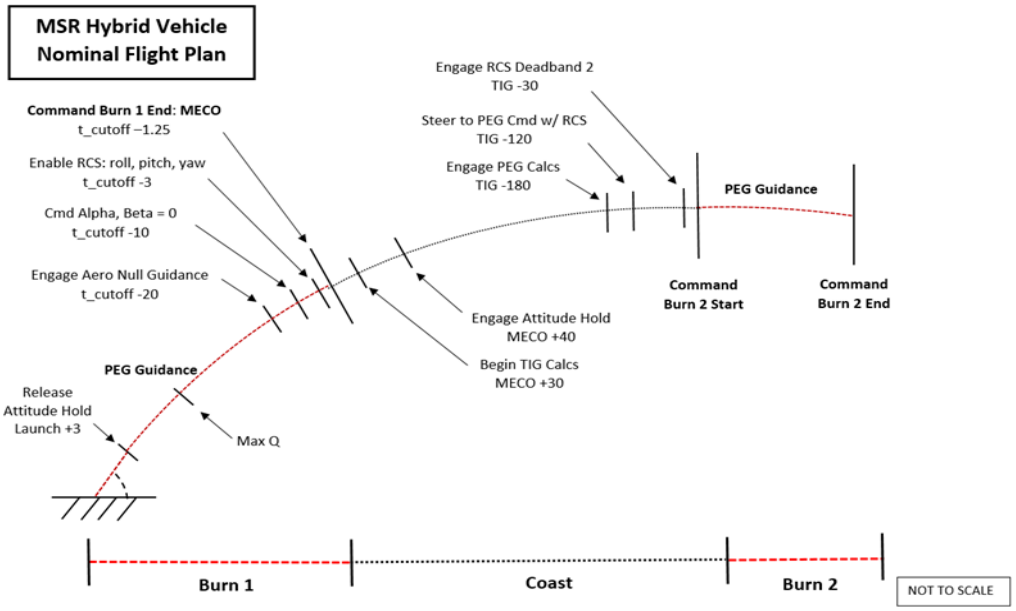


Figure 12. Hybrid Vehicle Flight Plan

dispersions resulted in semi-major axis constraints to be violated. All values of altitude, inclination, and eccentricity fell within constraints.

A GNC analysis was performed on the attitude control capabilities of the RCS and LITVC system. As mentioned in Section 6, LITVC is used for pitch and yaw control during engine burn, while RCS is used for roll control. RCS provides roll, pitch, and yaw control during coast. Six RCS thrusters were sized with two to control yaw and four to control pitch and roll. Two additional thrusters are present for fluid settling. After determining new guidance targets to reduce dynamic pressure and minimize angle of attack at MECO, some dispersed cases were found to still have an instability at the end of MECO. These could potentially cause the vehicle to develop large body rates. In all of these dispersed cases, the vehicle was able to recover as it moves out of the atmosphere and achieve the target orbit range. To attempt to mitigate the instabilities, the LITVC and RCS control systems were adjusted. Although some overall improvements were made, complete elimination of the unstable motion was not achieved. Improvements resulted from changes to the guidance and control system architectures, RCS thruster size, LITVC and RCS duty cycles, and timing of events. Further work will be required to address the instability in future analyses. Figure 13 shows the high body rates found on the vehicle after MECO.

A navigation sensor study was performed to select an appropriately capable IMU for the vehicle. Two sensors, a Honeywell HG5700 and a Sensonor STIM300, were compared based upon their physical size, mass, and overall performance. An overview of these sensors with respect to their nominal specifications are shown in Figure 14. Two comparable IMUs are included for reference.

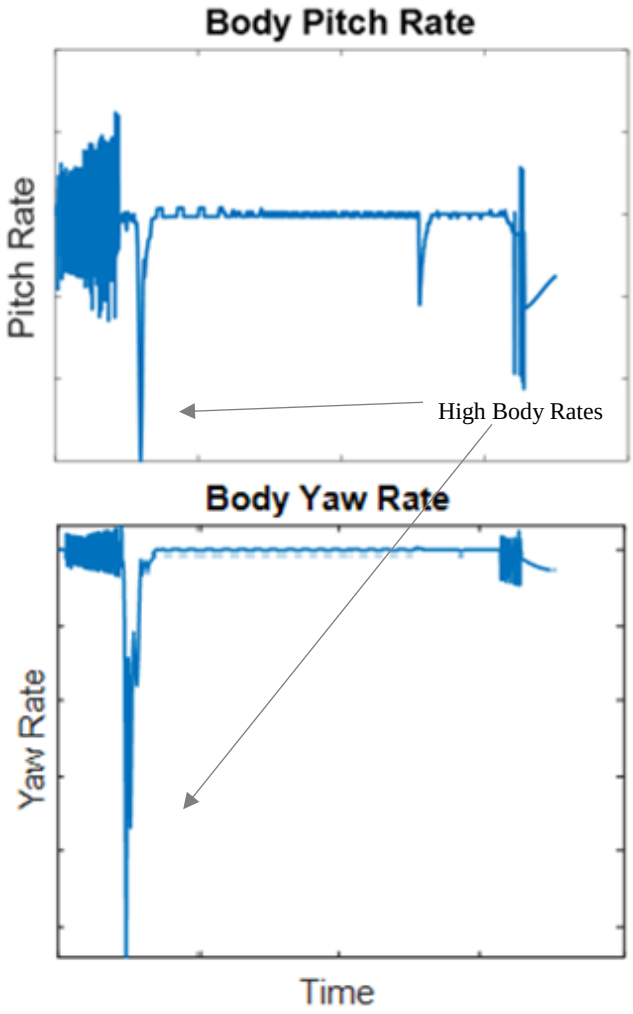


Figure 13. Post-MECO Body Rates

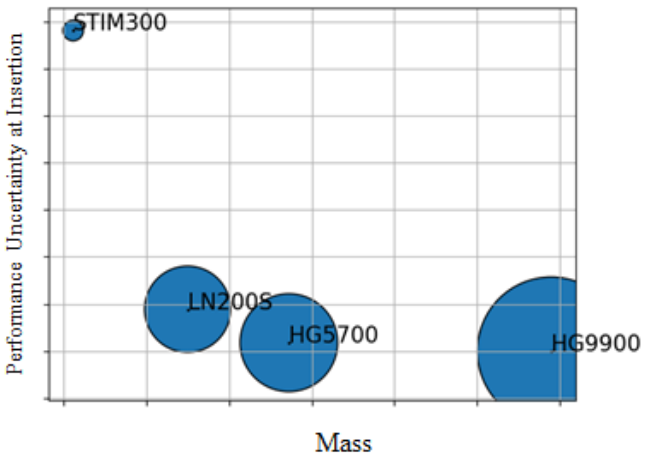


Figure 14. IMU Specifications

Figure 14 shows that as IMU performance capability increases, mass and physical size increase. As all three of these specifications are pertinent to the vehicle design, a Monte Carlo analysis was performed to further determine capability. This used a nominal 6DOF simulation base featuring a variety of errors such as bias, scale factor, internal misalignment, and white noise. Additionally, as mentioned in Section 4, a star tracker was introduced to the navigation system to further augment the IMU capability as needed. The system in general is highly sensitive to initial attitude knowledge.

The Monte Carlo analysis featured 2000 individual simulations for each IMU, with dispersed initial knowledge errors and sensor specifications. Cases both with and without star tracker integration were included. Without star tracker integration, the STIM300 IMU was found to only reach the target orbit with 9% of the cases, whereas the HG5700 achieved target orbit with 100% of the cases. With the addition of the star tracker, the STIM300 capability increased to 39% whereas the HG5700 remained at 100%. This showed that even with low initial attitude errors and the addition of a star tracker, the STIM300 has difficulty meeting the target insertion orbit. Overall, vehicle was more suited for the HG5700, or an IMU with similar specifications.

10. SUMMARY

The hybrid configuration of MAV successfully delivers a 14kg payload of 20 sample tubes to Martian orbit. Initial 6DOF analysis showed that size and weight constraints were met under nominal conditions. Later analysis determined that an increased mass was necessary, as the pre-TDK average Isp was over predicted. The results presented in this paper did not account for an updated mass and Isp. Target orbit was achieved in most dispersed cases, however, stability issues arise in some situations towards MECO. In the event of excess energy, the hybrid engine is capable of early shutdown. Further studies can expand upon the design of the hybrid configuration MAV and increase its maturity.

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BIOGRAPHY



Darius Yaghoubi *received a B.S. in Aerospace Engineering from North Carolina State University in Raleigh, NC in 2007. He has worked at NASA MSFC for 12 years. He has been an active member of the MAV team since February 2018, initially starting as the GNC lead and transitioning to the vehicle technical lead in October 2018. Prior to joining the MAV team, he worked as the lead pogo stability analyst on the NASA SLS program and supported separation and liftoff analysis on the NASA Ares program. He has also supported NASA groups in loads and dynamics, software integration, engineering testing, 3D printing, and deep space habitat. Aside from his technical work, Darius is an active member of the MSFC Speaker's Bureau and has represented NASA at a number of public outreach and speaking events*



Andrew Schnell *is a study lead and thermal system designer for Marshall Space Flight Center's Advanced Concepts Office. In over six years in Advanced Concepts, he has led ACO's design efforts on a variety of conceptual design studies including the Lynx X-Ray Observatory, Mars sample return missions, the Europa lander de-orbit stage, the HabEX telescope, and SLS's Exploration Upper Stage. He has also contributed thermal designs for deep space habitats, interstellar probes, solar sails, satellites, cubesats, SLS payloads, and ISS experiments. Prior to joining Advanced Concepts, Andrew was a member of NASA's Cryogenic Fluid Management team, where he managed the design and preparation of several cryogenic test articles. He holds a patent for the design of novel foam-rigidized inflatable structures. Andrew is a graduate of Tennessee Technological University.*