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MARS SAMPLE RETURN MARS ASCENT VEHICLE SEPARATION ANALYSIS UTILIZING THE CLVTOPS TOOLCHAIN

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A key element of the joint NASA and European Space Agency (ESA) Mars Sample Return (MSR) Campaign is the Mars Ascent Vehicle (MAV), which is being developed primarily by NASA Marshall Space Flight Center (MSFC), in association with NASA's Jet Propulsion Laboratory (JPL) and Langley Research Center (LaRC). The MAV is a Mars-launched rocket that is responsible for transporting soil samples collected by the Perseverance rover from the Mars surface into Martian orbit, where they will be captured by ESA's Earth Return Orbiter (ERO) for the return journey to Earth. The MAV design concept as developed during the MAV Systems Requirement Cycle (SRC) and Preliminary Design Cycle (PDC) consisted of a two-solid-stage configuration, where the second stage is completely unguided in order to reduce the mass of the vehicle and of the mission as a whole. The unguided second stage presents technical challenges for the stage separation event, as the second stage trajectory and the payload's ability to rendezvous with the ERO is extremely sensitive to disturbances during vehicle staging. The MSFC-developed CLVTOPS multibody dynamics toolchain was utilized to quickly assess multiple stage separation hardware options and to optimize the separation Concept of Operations (ConOps) in order to ensure successful near-field stage separation performance and maximize the orbital accuracy of the payload. This paper will describe how the CLVTOPS toolchain was used to assess the MAV stage separation event and inform and optimize the MAV design and ConOps.

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INTRODUCTION

Conducting a rocket launch and operations is always a challenge. Moving the operations to the surface of another planet, far from human influence and the known Earth environment, is exponentially more complex, but NASA has undertaken this challenge with the design of the Mars Ascent Vehicle (MAV). MAV is a two-stage, small payload, partially guided rocket designed to deliver soil samples to Mars orbit from the Martian surface. MAV is a critical system of the Mars Sample Return (MSR) mission being spearheaded primarily out of NASA's Jet Propulsion Laboratory (JPL), although much of the MAV design work is being led by Marshall Space Flight Center (MSFC). MSR orchestrates the Mars 2020 Perseverance rover, the European Space Agency (ESA) Earth Return Orbiter (ERO), and JPL's Sample Retrieval Lander (SRL), which contains an ESA Sample Transfer Arm (STA) and the MAV. All these components need to operate and coordinate with a substantial Earth communication delay and in the hazardous Martian environment.

The broad strokes of the MSR mission are as follows. Perseverance has been collecting and storing soil samples as part of its mission, which are encapsulated and left on the Martian surface. The SRL will be sent to Mars to land in the vicinity of packaged samples, collect the samples, and load the samples as payload into the MAV. MAV will launch the payload into a specific Mars orbit, where it will rendezvous with ESA's ERO for a return trip to Earth.

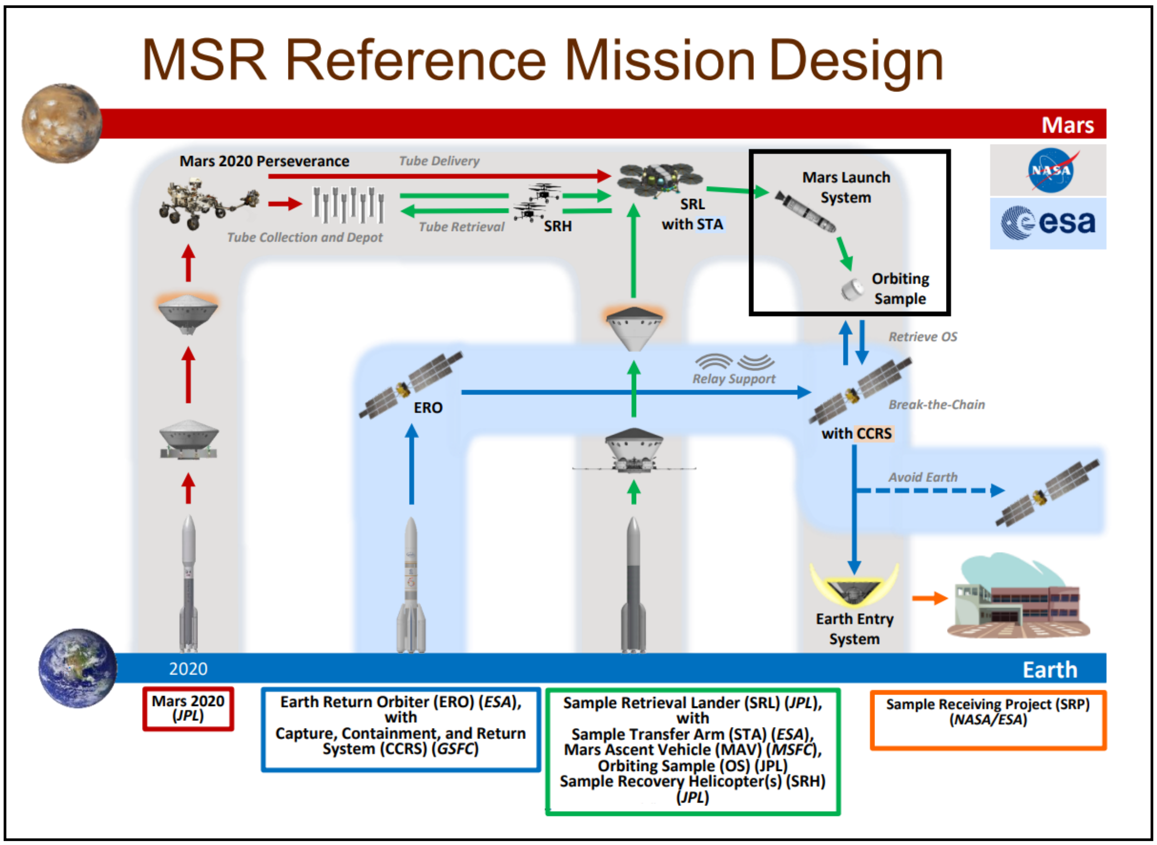

Figure 1. MSR ConOps with MAV portion boxed in black. Reproduced from Rountree et al.[1]

Figure 1 provides a visual representation of the elaborate MSR mission architecture. With an architecture this complex, many things need to go right for the mission to succeed. One particular challenge, and the topic which drove the analysis discussed in this paper, is ensuring the MAV sample payload achieves the proper orbit despite perturbations caused by staging. The details of the design and operation of the MAV are still preliminary, however; the question of whether MAV is capable of meeting its mission obligations must constantly be reframed and recontextualized as the design of the launch vehicle evolves.

MSFC has deep expertise in launch vehicle design and specific expertise in Guidance, Navigation, and Control (GN&C), and as such is well-positioned to work on this problem. A robust and flexible launch vehicle simulation framework is an essential capability when performing this type of separation analysis. Such a framework must strike a balance between competing factors; of course it must provide accurate physics, but it must also be computationally efficient enough to reassess vehicle behavior and orbital insertion characteristics on an as-needed basis in a rapidly-evolving program. It must also be easy to change the simulation as the design changes, and the tool must provide useful data and visualizations to iteratively inform the design. The MSFC-developed CLVTOPS toolchain provides such a framework, combining six degree of freedom (6DOF) trajectory simulation with high-fidelity vehicle geometries and relevant physics to accurately model vehicle behavior from launch to orbital insertion, including during separation events.[2] Thanks in part to the CLVTOPS toolchain, MSFC has advanced the MAV concept through Preliminary Design Review (PDR) in April 2023 despite fundamental reworks to the vehicle architecture from the original conception, including the removal of GN&C capabilities in the orbital insertion stage.

This paper provides an example MAV stage separation analysis, which demonstrates both the critical importance of accurately modeling separation dynamics and the capabilities of the CLVTOPS toolchain. First, the latest MAV architecture and separation system will be discussed. Then, an overview will be provided of the simulation framework used to model MAV separation dynamics, the CLVTOPS toolchain. Next, the translation of the MAV architecture into the toolchain is described. Finally, key input models impacting separation will be discussed, with an emphasis on how system stressors were identified and mitigated using the CLVTOPS toolchain.

MARS ASCENT VEHICLE ARCHITECTURE

The Mars Ascent Vehicle (MAV) is the launch vehicle designed to transport Martian soil samples from the Mars surface to Mars orbit as part of the MSR mission. The preliminary architecture for the MAV is a two-stage guided-unguided vehicle. The lower stage, called Stage 1 or ST1, consists of a solid rocket motor with a single engine for primary propulsion and Thrust Vector Control (TVC), and Reaction Control System (RCS) thrusters for additional control. See Figure 2 for a layout of the MAV vehicle architecture.

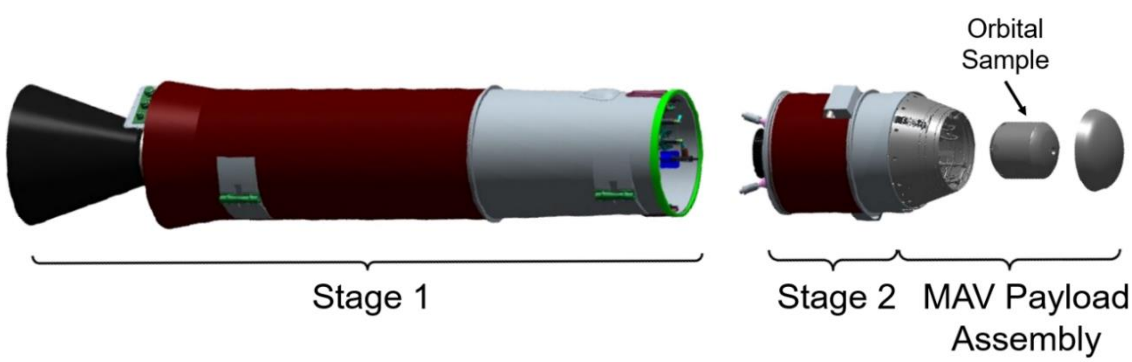

Figure 2. Architecture of the MAV vehicle. Reproduced from Figure 1 of Yaghoubi et al.[3]

The purpose of the MAV Stage Separation event is to free Stage 2 (also referred to as ST2) from Stage 1 to continue the MAV mission while minimizing the difference between the optimal Stage 2 thrust direction and the actual applied post-separation thrust vector (a metric referred to as "ϴ2" or "pointing error"). Several subsystems work in tandem during the MAV stage separation event to achieve this purpose. Some important considerations when designing the separation subsystems center on the system hardware and mechanisms, and how hardware choices impact the performance of the separation event. Other considerations are related to event timing, and how the precise orchestration of the subsystems impacts the separation. The following two subsections will provide a high-level overview of how hardware and timing considerations inform the Stage Separation Concept of Operations (ConOps).

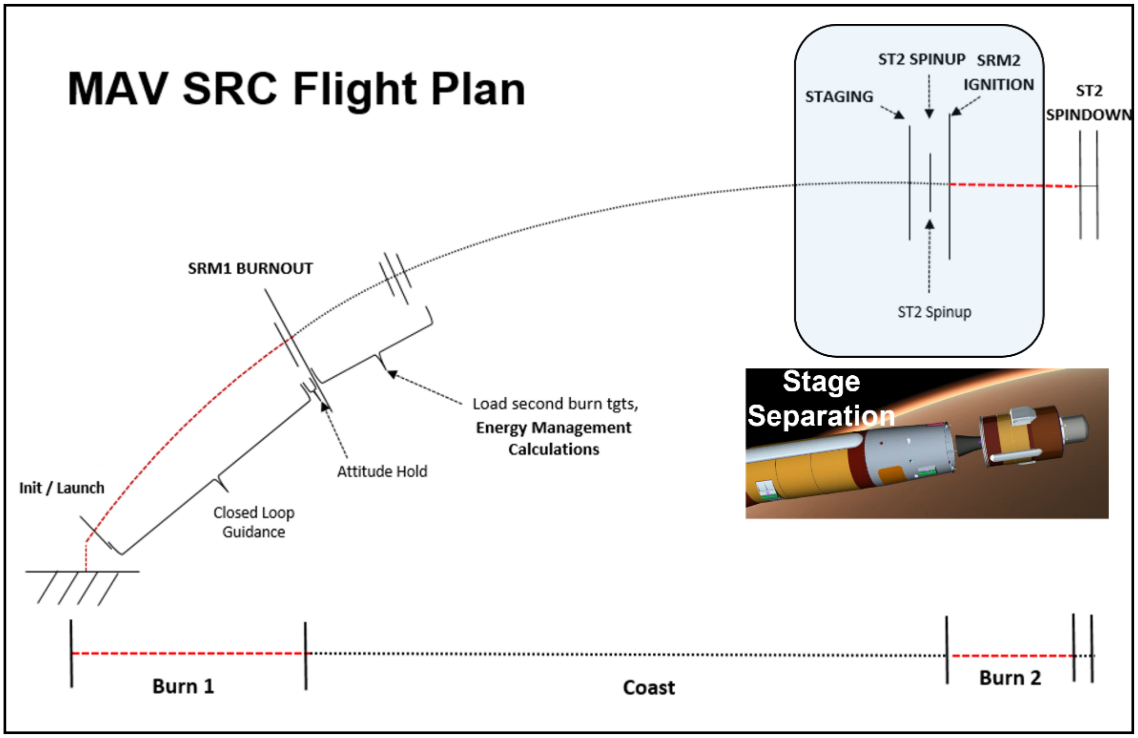

Figure 3. MAV ConOps from launch to the Stage 2 Spin-Down.

Figure 3 shows the mission timeline for MAV from launch to the end of payload separation. It is important to note that there are other critical separation events in the MAV ConOps beyond stage separation, namely the initial Vertically Ejected Controlled Tip-Off Release (VECTOR) launch and the final Orbital Sample (OS) separation between Stage 2 and the payload. However, this paper will focus only on considerations related to the Stage Separation event, except where the separation dynamics at Stage Separation are driven by OS considerations; in those cases, there will be a brief discussion of how the Stage Separation dynamics impacts OS.

MAV Stage Separation Hardware Configuration

During the initial ascent, the separation system must keep Stage 1 (lower guided stage) and Stage 2 (upper unguided stage) mated, and then sever the connection at the proper moment during the separation event. After mating severance, the system must provide an impulse to move the stages apart from each other. Finally, as the stages separate, umbilical connections between the stages must be disconnected while imparting minimum disturbance to Stage 2.

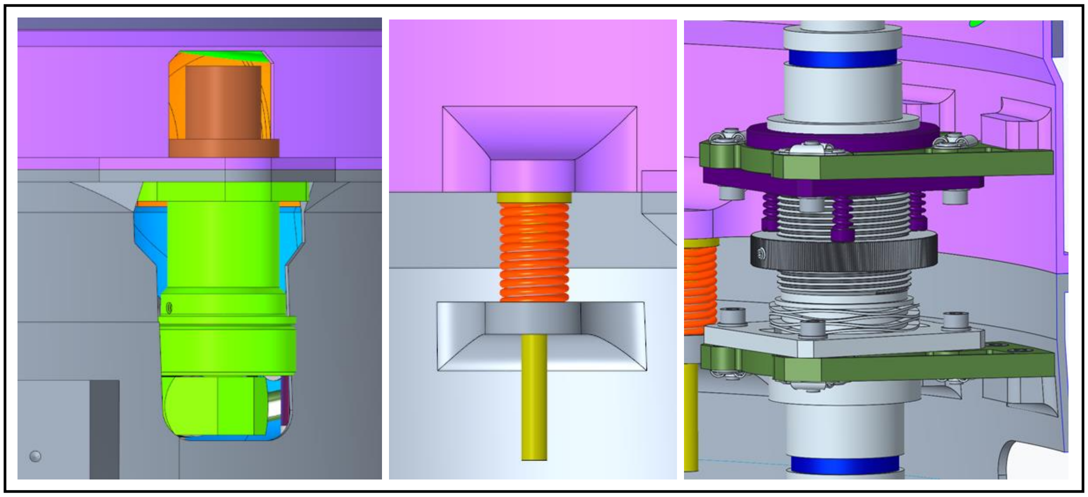

Figure 4. Separation subsystems for MAV Stage Separation for PDR: LSSNs (left), Pusher Springs (center), and Adjustable Force Connectors (right).

Figure 4 provides details of the MAV separation hardware subsystems as used for the April 2023 MAV Preliminary Design Review (PDR). The ascent mating and severance is handled using Low Shock Separation Nuts (LSSNs). Impulse between the stages is applied from six pusher springs, which impart forces as soon as the stage connection is severed. The umbilicals use Adjustable Force Connectors (AFCs), which can be tuned to mitigate forces caused by the umbilicals pulling apart. This particular configuration is the final result of several years' worth of analysis and trade studies using the CLVTOPS toolchain, a selection of which are detailed in this paper. A more in-depth discussion of how this configuration was selected is provided in the *MAV Stage Separation Sensitivity Studies* section.

MAV Staging Operations and Timing

Directly after stage separation, there are also some necessary operations Stage 2 must take to maintain stability and attitude, and these operations must be carefully timed to ensure the final orbit is reached without compromising near-field hardware clearance. The first operation is Stage 2 spin up, which is used to stabilize the unguided MAV stage and payload. Two solid Spin-Up Motors are used to initiate the spin, and they must be timed to stabilize the Stage 2 trajectory as quickly as possible without sacrificing positive clearance between the separating Stages. The second operation is the Solid Rocket Motor 2 (SRM2) burn, which provides the energy required to achieve the target payload orbit. The SRM2 burn must initiate at a precise timing in the vehicle precession, again to minimize pointing error, and must also fire at a sufficient distance from Stage 1 to prevent upstream effects on Stage 2 from SRM2/Stage 1 plume recirculation. These operations will be discussed in more detail in the *MAV Stage Separation Sensitivity Studies* section.

Importance of Separation Dynamics Modeling to MAV Mission Success

Separation dynamics modeling is critical to the success of MAV for a few reasons. Broadly speaking, separation dynamics is essential for launch vehicle success in general; in fact, a 2015 NASA study led by Ames Research Center found that stage separation issues were the second leading cause of US launch vehicle failures over the span from 1980 to 2015, surpassed only by engine failures.[4] Beyond the general difficulty of rocket staging, though, MAV also has many specific features that require robust and high-fidelity separation dynamics modeling.

For one, MAV is rather small, with low mass and small moments of inertia. With such a sensitive system, even minor disturbances from the separation system can have a large effect on the system behavior and final orbit. Secondly, the whole MAV system has an extended lifetime, and will undergo extended exposure to low temperatures, high radiation, and other environmental dangers of the Martian surface for up to several years before launch, which presents challenges for all MAV's subsystems including the separation system. Lastly, and most critically, the upper stage of MAV is unguided throughout the SRM2 burn and long coast before OS separation. The absence of GN&C on the second stage constrains the whole system, as any disturbances accrued after separation from the first stage cannot be mitigated, and all potential off-nominal performance cases must be well-understood in advance such that the guided first stage can properly position the second stage for burn and payload separation before the first and second stages separate.

This host of considerations requires a capable modeling and simulation pipeline to ensure adequate MAV performance. The CLVTOPS toolchain offers such a pipeline, and was used extensively for MAV Stage Separation design, optimization, and verification. The next section will describe the CLVTOPS toolchain and its capabilities in more detail.

OVERVIEW OF THE CLVTOPS TOOLCHAIN

The CLVTOPS toolchain consists of a suite of simulation, visualization, and post-processing tools which are extremely helpful for studying vehicle dynamics during launch, ascent, and spaceflight.[2] The CLVTOPS toolchain has end-to-end simulation, visualization, and post-processing capabilities for multibody dynamical systems. The core of the toolchain is a Kane's Method[5] implementation called TREETOPS[*], and extended capabilities are "wrapped" around the core in a nested manner. Figure 5 shows the structure of the CLVTOPS toolchain.

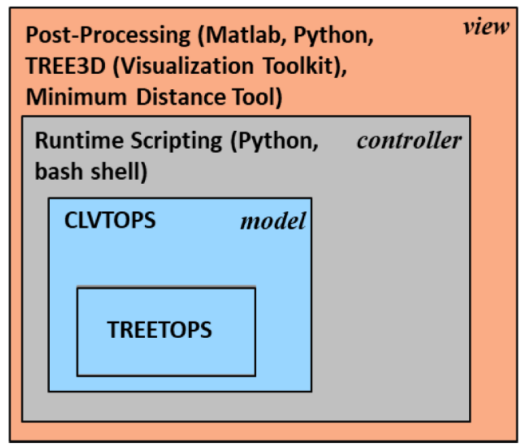

Figure 5. Architecture of the CLVTOPS toolchain, reproduced from Figure 6 of Burger et al.[2]

At MSFC, the CLVTOPS toolchain is primarily used for minimum clearance analysis during separation events, a task for which it is well-suited. The toolchain has many uses and capabilities beyond clearance analysis, however; it is possible to complete an end-to-end vehicle simulation from launch to mission end. Additionally, the toolchain can initialize a state from other simulation tools, which allows for high-fidelity modeling during specific events without reproducing the effort of creating a full simulation. For MAV, CLVTOPS is used for analyzing clearance during the stage and payload separation events and for confirming the sample payload achieves the required orbit for ERO rendezvous.

CLVTOPS, the Simulation Driver

CLVTOPS is the simulation driver and the eponymous element of the CLVTOPS toolchain. In CLVTOPS, multibody models can be constructed to represent vehicle stages, and then apply forces and moments to assess the system response. A vehicle model in CLVTOPS consists of:

- bodies, which can be assigned various properties like a mass and center of gravity,

[*] https://software.nasa.gov/software/MFS-33566-1

- nodes, which are placed on bodies and used to track specific locations,
- hinges, which connect bodies together at nodes,
- and devices, which represent pre-defined mechanisms such as springs and actuators.

Other simulated entities can be used to further customize a multibody system, such as custom function generators. Once the multibody model and forces are established, CLVTOPS also provides the dynamics driver which propagates the system in time.

Tree3D, the 3D Visualization Kit

Tree3D* is a trajectory visualization tool developed by the EV42 Liftoff and Separation Dynamics team at NASA MSFC which combines 3D hardware models and simulation data to create an animation of system behavior over time. Tree3D animations generally serve to supplement other data and statistical analyses when post-processing simulation data, and they are used extensively to help communicate results. These animations allow users a simple and intuitive way to visualize system behavior in 3D space.

Figure 6. Example Tree3D Visualizations of MAV Stage Separation Event.

Figure 6 provides an example of a Tree3D animation of the MAV Stage Separation event, split into individual frames. Animations such as this provide a quick and easy way to check whether the MAV simulation has been set up correctly; simply looking at the body motion in 3D space can identify issues such as misapplied forces, incorrect reference frames, or other common modeling mistakes. Tree3D is also capable of plotting force vectors along with the simulated bodies, which is also helpful for confirming simulation behavior.

Minimum Distance Tool, the Proximity Calculator

The Minimum Distance Tool (MinDistTool) is software developed as a component of the CLVTOPS toolchain which is used to assess clearance between triangulated meshes. All MAV stage Computer-Aided Design (CAD) models are converted into 3D meshes and fixed to appropriate CLVTOPS simulation body nodes; MinDistTool then computes the closest distance between mesh pairs or indicates a recontact as necessary. Identifying clearance with the MinDistTool is an essential component of simulation of the MAV Stage Separation, as any contact during separation is mission critical.

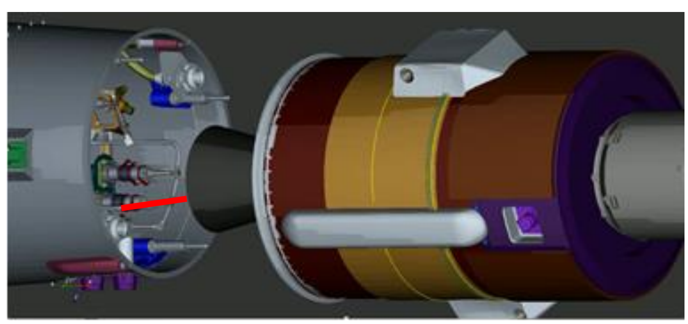

Figure 7. Example of MinDistTool output (red) visualized in Tree3D during Stage Separation.

* https://software.nasa.gov/software/MFS-34076-1

Figure 7 provides an example of the MinDistTool-provided minimum distance line as visualized with the MAV stages in Tree3D. The output integrates with Tree3D to visually plot the minimum distance line with relation to the simulated bodies through time. Again, this visualization capability is hugely beneficial to the design and analysis process, as it provides a clear indication of where clearance is tightest between the bodies, and quickly demonstrates where additional design work may be necessary to improve clearances.

Post-Processing Scripts

The final stage of the toolchain is a collection of custom post-processing scripts which are used to analyze outputs from CLVTOPS and MinDistTool, such as visualizing dynamical parameters of interest (forces, velocities, displacements, accelerations, etc.) throughout the simulation, plotting the change of minimum clearance between bodies, or calculating the order statistics used to quantify results. In general, the outputs of these scripts are ultimately used to verify concurrence with requirements and assess vehicle performance. For MAV Stage Separation, custom scripts were used to calculate and visualize Stage 2 orbital performance, and examples of these outputs will be provided in the *MAV Stage Separation Sensitivity Studies* section.

DEVELOPMENT OF THE MAV MODEL IN THE CLVTOPS TOOLCHAIN

The MAV Stage Separation simulation does not span the whole MAV trajectory. Rather, CLVTOPS is instantiated using simulation output from the official, primary MAV GN&C 6DOF simulation tool, named the MAV Analysis Tool in Simscape (MANTIS)[6] ; this co-operability of CLVTOPS with other simulation tools is very convenient for quick assessments of staging events without requiring a complete remake of the entire simulation. For MAV Stage Separation analysis, the CLVTOPS simulation starts just prior to staging and continues until the SRM2 burn.

Because the CLVTOPS simulation window is small when assessing hardware clearance, several simplifications can be made that are valid during the Stage Separation event, such as assuming constant mass properties and ignoring gravitational acceleration. Although some of the details of the system are neglected in the Stage Separation model, it is important to note that the CLVTOPS toolchain is capable of very high-fidelity representations, and more sophisticated models can be developed and integrated as necessary for a particular problem statement. For example, the CLVTOPS simulation used for final orbital assessment extends from Stage Separation to Orbital Stage separation; because this simulation must capture a much longer duration, higher fidelity models are included in that simulation, such as the SRM2 burn and residual thrust, changes in mass, center of gravity (CG) and inertia, energy dissipation during coast, gravitational acceleration, and spin-down dynamics.

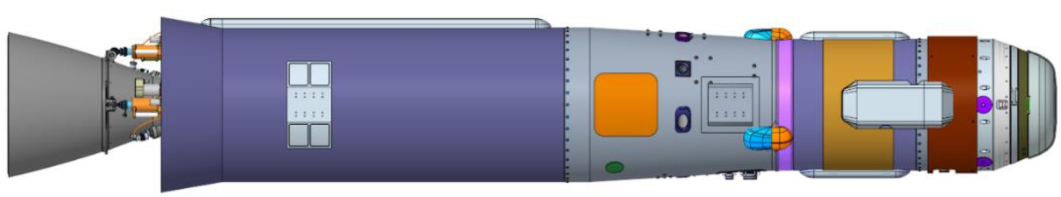

Figure 8. Simplified MAV OML Model used for CLVTOPS Analysis.

Figure 8 shows the simplified geometry model of MAV that was incorporated into CLVTOPS and used with the MinDistTool. It is common to reduce complex CAD representations of the real hardware into simplified Outer Mold Line (OML) representations; because such models capture the outermost geometry of the complex CAD model, they provide a simpler, less computationally intensive representation that is still accurate for clearance analysis.

Figure 9 provides an interior view of the Stage 2 nozzle mated inside the Stage 1 hardware. The CLVTOPS clearance meshes include the interior subsystems which could reasonably contact the Stage 2 nozzle during Stage Separation. Because the Stage 1/Stage 2 interface is the region where recontact is most likely to occur during separation, the clearance meshes are relatively more complex in this region compared with the OML strategy used for most of the MAV systems.

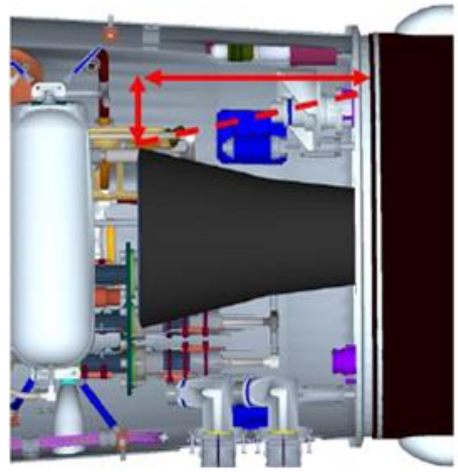

Figure 9. Interior view of the Stage 1/Stage 2 separation interface used for clearance analysis; flyout angle provided in red. Reproduced from Figure 32 of Yaghoubi and Maynor.[3]

When modeling the Stage Separation event dynamics, MAV is represented as two rigid bodies in CLVTOPS with constant mass properties. Before separation, these two bodies are mated at the LSSN locations using simulated linear spring-damper devices with very high stiffness and damping; these connections ensure the body nodes at these locations maintain a very small relative displacement before severance. At separation, the stiffness and damping of these connections is set to zero, which allows the stages to move apart. A timing dispersion is applied to each spring-damper connection to represent the simultaneity error of the separation system.

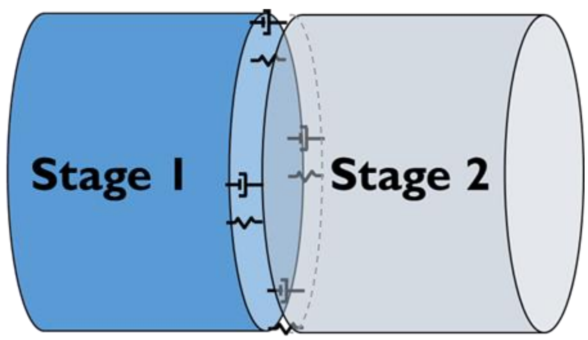

Figure 10. Foundational model of the MAV during Stage Separation.

Figure 10 provides an image of the basic elements of the CLVTOPS model. From this simple foundational model, additional features are added which tune the simple model to behave like the actual MAV system. For instance, each body is given the mass properties, CG, and rotational inertias of each MAV Stage. Furthermore, the masses, inertias, and locations of the CGs on each body are dispersed to capture uncertainty in the manufacturing, stacking, and mass of each individual component. Finally, forces and moments representing the separation system design are applied to appropriate locations on each body throughout the separation event, which drive the dynamics of the model. These force and moment models are often taken directly from the component manufacturer, but sometimes are estimated where specific data is not available. For example, linear actuators are placed at the location of the pusher springs and apply forces according to a spring-force-vs-stroke-length force profile developed to closely match the actual springs. Dispersions are applied to the spring properties to account for differences between the physical springs and the uncertainty of the exact spring response during the mission. By closely capturing mass, rotational inertia, CG, and separation forces, the model behavior faithfully represents the MAV system design during Stage Separation.

The CLVTOPS toolchain was also used to generate a Keep-Out Zone (KOZ) for MAV hardware which was guaranteed to clear based on the simulated dynamics of the separation. This KOZ accounts for all the modeled separation dynamics, including tipoff rates, separation springs, spin-up timing and burn, and SRM2 burn timing, which are discussed in detail in the next section.

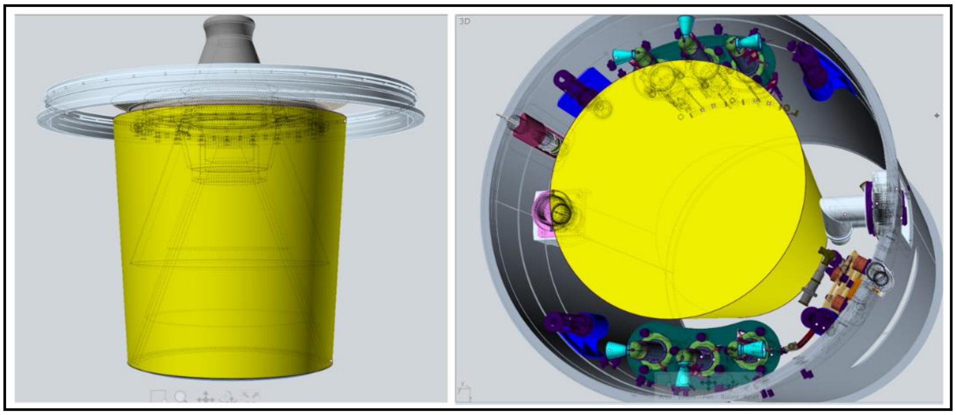

Figure 11. KOZ developed with the CLVTOPS Toolchain to protect hardware clearance.

Figure 11 shows an example of a KOZ developed for MAV stage separation. The KOZ consists of a simplified envelope which captures all the trajectories that are swept out by Stage 2 hardware during the Monte Carlo analysis. The KOZ will be used for later iterations on the MAV design to ensure clearance will be acceptable even as the design evolves.

MAV STAGE SEPARATION SENSITIVITY STUDIES

MAV Stage 2 is very sensitive to off-nominal conditions due to its low mass, long flight time, and lack of GN&C. The following sections will discuss some of the primary sensitivities of the MAV Stage Separation event, how these sensitivities impact the MAV mission, and how the CLVTOPS toolchain was used to identify these sensitivities and inform MAV design for sensitivity mitigation.

Tipoff Rates

To ensure Stage 2 reaches the target ERO rendezvous orbit, the mated stages must be disconnected in such a way that Stage 2 continues to point in the direction dictated by Stage 1 guidance (for a detailed discussion of Stage 1 guidance, see Everett et al.)[7] The details of how the mating hardware disconnects have a large impact on the final Stage 2 orbit due to the sensitivity of Stage 2 to "tipoff rates," which is a term for the attitude rates imparted to Stage 2 during the stage separation event. Any forces imparted by the separation system will apply at the aft end of Stage 2 and induce a moment about the CG, which can change the pointing direction. These forces can come from the mating and severance system, the pusher springs, or the umbilical disconnects. Additionally, any difference in release timing between mating hardware (called *simultaneity*) will also cause a rotation around whichever mechanism releases last.

Several separation system configurations were assessed for MAV, and tipoff rates were of primary concern. Non-Explosive Actuators (NEAs) were examined first; they imparted small separation forces, but ultimately their simultaneity error had the potential to result in unacceptable tipoff rates. Next, a clamp-band and bolt cutter design was assessed, which had excellent simultaneity due to only having a single release mechanism, but was deemed inadequate due to the large tipoff moment caused by the lateral forces they applied at the separation plane. For the April 2023 PDR, Low Shock Separation Nuts (LSSNs) were selected as striking the correct balance between separation forces, simultaneity, and other important mission considerations. For a more complete discussion of these considerations, see Yaghoubi and Maynor.[3]

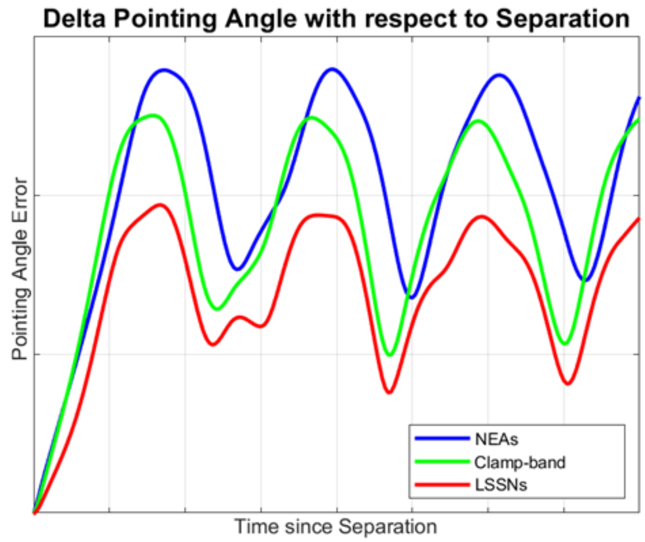

Figure 12. Comparison of highest pointing error exhibited by LSSNs (red), NEAs (blue), and clamp band (green).

Figure 12 compares Stage 2 dispersed pointing errors for NEAs, clamp bands, and LSSNs. The CLVTOPS toolchain was used to collect the data and generate the plots. The generation of this data using CLVTOPS was a major contributor to the separation system design process, and Monte Carlo simulations were used to model and check the performance of each separation system design. Note also that these different separation system configurations each used an optimized spring pusher energy and spin-up timing for that system such that best expected performances could be compared. From the pointing error plots, it is clear that LSSNs provide the smallest pointing error after the Stage 2 spin-up out of the three separation hardware designs.

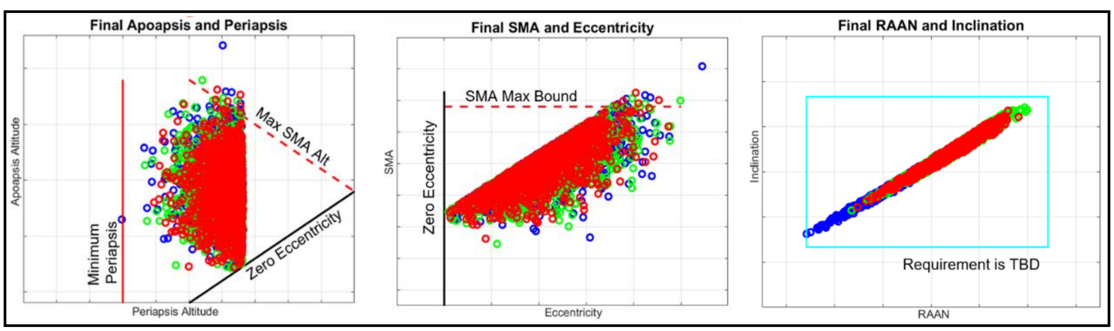

Figure 13. Comparison of final Stage 2 orbit for various separation hardware: LSSNs (red), NEAs (blue), clamp bands (green).

Figure 13 shows the spread of dispersed final Stage 2 orbits reached for each of the assessed separation systems, along with preliminary performance bounds. From the spread of orbits reached by Stage 2, the magnitude of the tipoff rates at separation clearly has a major impact on the final orbit of the payload. The LSSNs provide the tightest spread of final orbits compared to the NEAs and the clamp band designs.

Separation Springs

The system for MAV stage separation employs pusher springs to provide impulse between Stage 1 and Stage 2 during the separation event. The springs begin compressed, so they are free to extend as soon as the connection between the stages is severed. The action of the springs is the main reason that separation system simultaneity is so important; the restoring of the compressed springs can cause a hinging effect around the last connection in the milliseconds before it disconnects, resulting in a moment around that connector. The resulting moment can impact the final post-staging pointing error, called "ϴ2." Figure 14 provides a diagram of the mechanics of how simultaneity differences cause tip-off moments of MAV Stage 2 as the springs decompress.

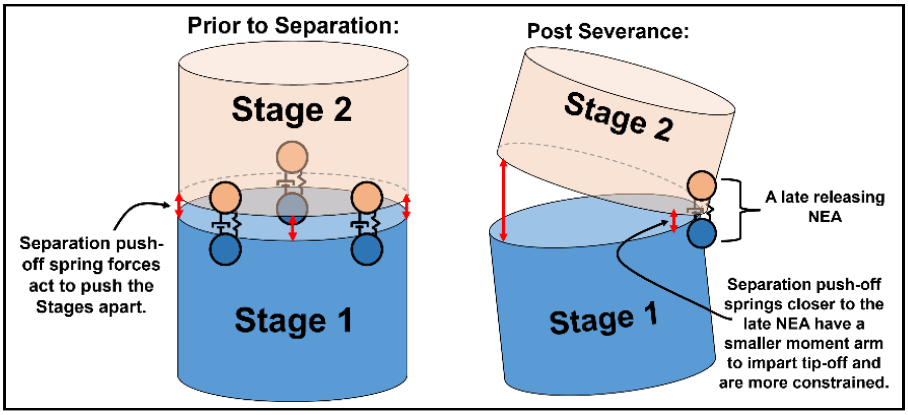

Figure 14. Tipoff Resulting from Simultaneity Differences.

The spring system design also impacts the timing of separation operations. For instance, the energy provided by the springs determines the time-to-clear (TTC) of Stage 2 relative to the Stage 1 hardware, which in turn determines when other critical separation operations can start, such as spin-up and SRM2 burn. A study was conducted to optimize the spring energy for best separation performance.

Figure 15 demonstrates the relationship between pointing error and the spring energy, where a clear minimum emerges. Because spin-up does not occur instantaneously, a higher tipoff rate (caused by higher spring energy) continues to build pointing error during the spin-up, which accounts for the larger error as spring energy increases to the right of the minimum. To the left of the minimum, the long TTC caused by low spring energy delays the spin-up burn, which delays Stage 2 stabilization and causes higher post-separation pointing error. Balancing the spin-up timing and tipoff rate minimizes overall ϴ2 error during Stage Separation.

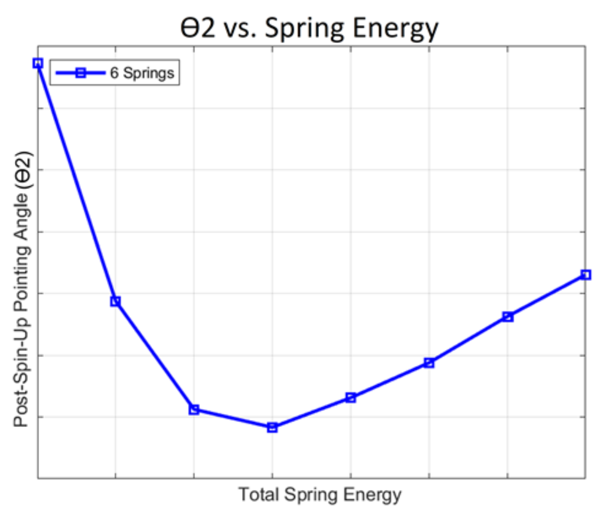

Figure 15. Highest ϴ2 error for LSSN configuration as a function of spring energy.

The physical characteristics of the pusher springs in the separation system also bring a host of considerations which must be modeled. For example, each spring may have slightly different performance, which can cause asymmetry in the provided impulse to Stage 2. Coupling the spring-to-spring differences arising from manufacturing and materials considerations with the long period of compression and exposure to cold environments inevitably leads to slight variations in performance that must be estimated in advance.

Besides pre-selecting the springs to be as similar as possible, the primary mitigation for spring-to-spring differences is increasing the number of springs in the separation system. As can be seen in Figure 16, increasing the number of springs reduces the ϴ2 error of Stage 2. The additional springs reduce the impact of off-nominal states associated with any given spring; in other words, the additional springs cause the behavior of the set of all springs to regress towards the mean. There is a trade-off present in the inclusion of additional springs, however, as each additional spring and associated support hardware increases the mass of Stage 2. MAV has a strict mass budget, so it is necessary to balance the benefit of additional springs against the overall system cost of adding mass to the separation system.

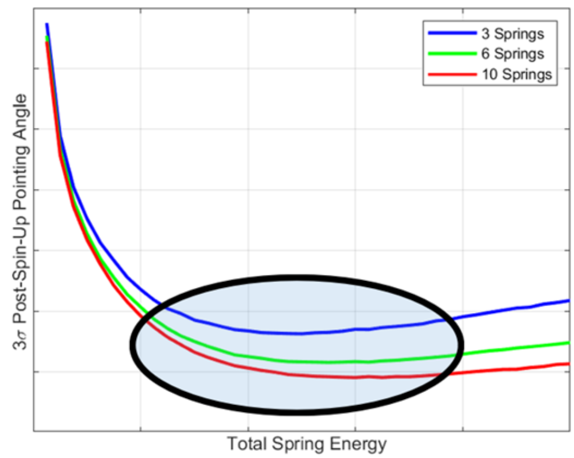

Figure 16. Reduction in ϴ2 error as additional separation springs are added.

Spin-Up Timing and Burn

After the separation springs have imparted impulse to the stages, Stage 2 must complete the rest of the MAV mission without GN&C. It is necessary, then, to quickly stabilize the pointing attitude of Stage 2 to preserve the attitude dictated by Stage 1 prior to separation. The stabilization mechanism for Stage 2 is rotation imparted by two Spin-Up Motors. An earlier spin-up results in a faster stabilization, which generally protects Stage 2 ϴ2 performance and orbital insertion accuracy; however, there is overlapping hardware between the stages near the separation plane which may prevent spinning up before the nested Stage 2 hardware (e.g., the SRM2 nozzle) has fully cleared the MAV interstage.

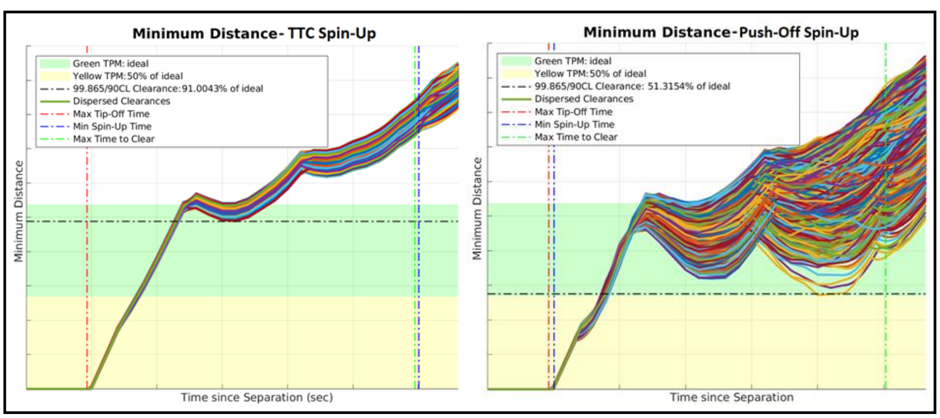

Figure 17. Dispersed minimum clearance with spin-up occurring after Stages clear (left) compared to spin-up directly after push-off (right).

Stage 2 spin-up has a large impact on the clearance between the hardware stages, as can be seen in Figure 17. The left plot in Figure 17 shows the minimum distance computed with the MinDistTool between the separating MAV stages assuming spin-up occurs at TTC; the right plot shows the same computation when spin-up occurs directly after the springs push off and before all the mated hardware has cleared. And, because the clearance is small even under ideal conditions (see Figure 9), it is imperative that the spin-up is studied in detail to optimize timing and performance.

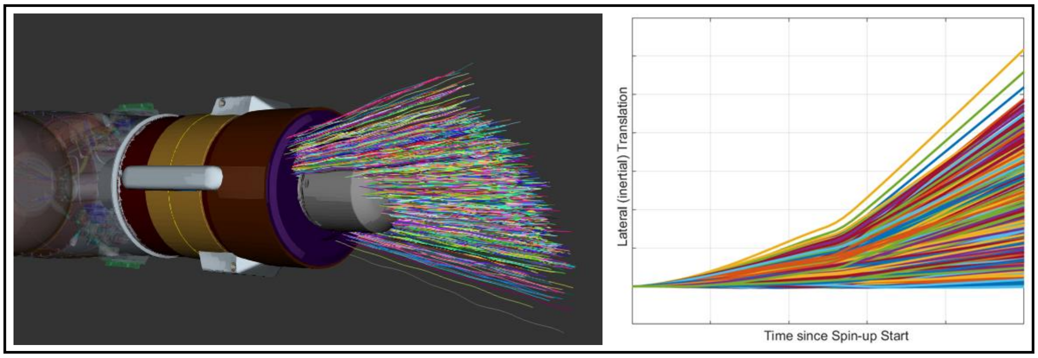

Figure 18. Lateral Motion Caused by Spin-Up.

The Spin-Up Motor burn also produces an unintended lateral force, which must be factored into the clearance dynamics. The left plot in Figure 18 provides a visual representation of the lateral biasing present in the flyout trajectories of Stage 2 which appeared during Monte Carlo simulation; the right plot shows the spread of lateral translations caused by the lateral force, where a horizontal line would indicate zero translation. This lateral force does not appear during nominal spin-up burn but can appear when differences in burn rate exist between the two Spin-Up Motors. The separation timeline must be robust to this lateral motion, which slightly delays the spin-up timing and results in a larger ϴ2 error.

SRM2 Burn Timing

Finally, the main engine of Stage 2 ignites, propelling the upper stage to the ERO capture orbit. Two main sensitivities were identified during this operation in the separation timeline, and both are related to the firing timing of the SRM2.

First, it is important to mitigate adverse SRM2 plume recirculation off of Stage 1, which can impact Stage 2 and impart unintended forces. Plume reflection is primarily mitigated by waiting for sufficient distance between the stages before firing the motor. A CFD study was conducted to assess the impact of SRM2 plume recirculation onto Stage 2 after the stages had separated a short distance.

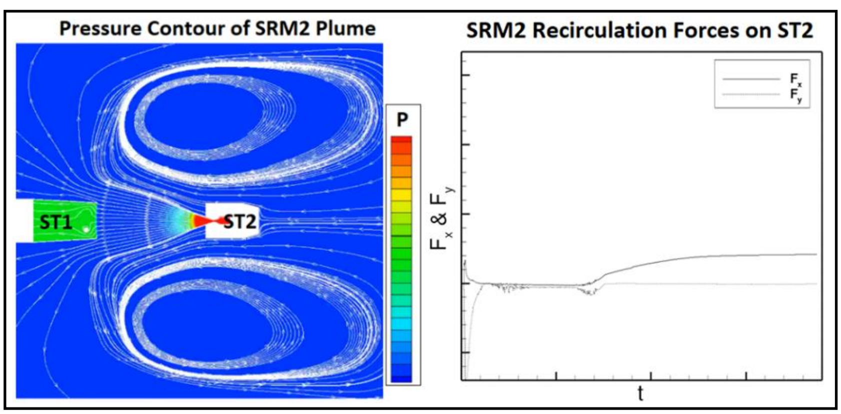

Figure 19. Pressure contour of SRM2 plume during startup transient (left), and axial and lateral forces imparted to Stage 2 by SRM2 plume (right).

As can be seen in Figure 19, the impact of the SRM2 plume reflecting from Stage 1 back onto Stage 2 is negligible once the stages are a short distance apart. The left plot shows the pressure contour during the startup transient, and the right plot shows the axial and lateral force on Stage 2 caused by the SRM2 plume only; a recirculation bubble is visible in the pressure contour, but the side force impacting Stage 2 is near zero throughout the transient.

The second timing consideration is related to the spin dynamics of Stage 2. After spin-up, Stage 2 exhibits a precession around the primary axis of rotation. This precession results in a periodic pointing error, as measured between the MAV Stage 2 longitudinal axis and the pre-separation attitude.

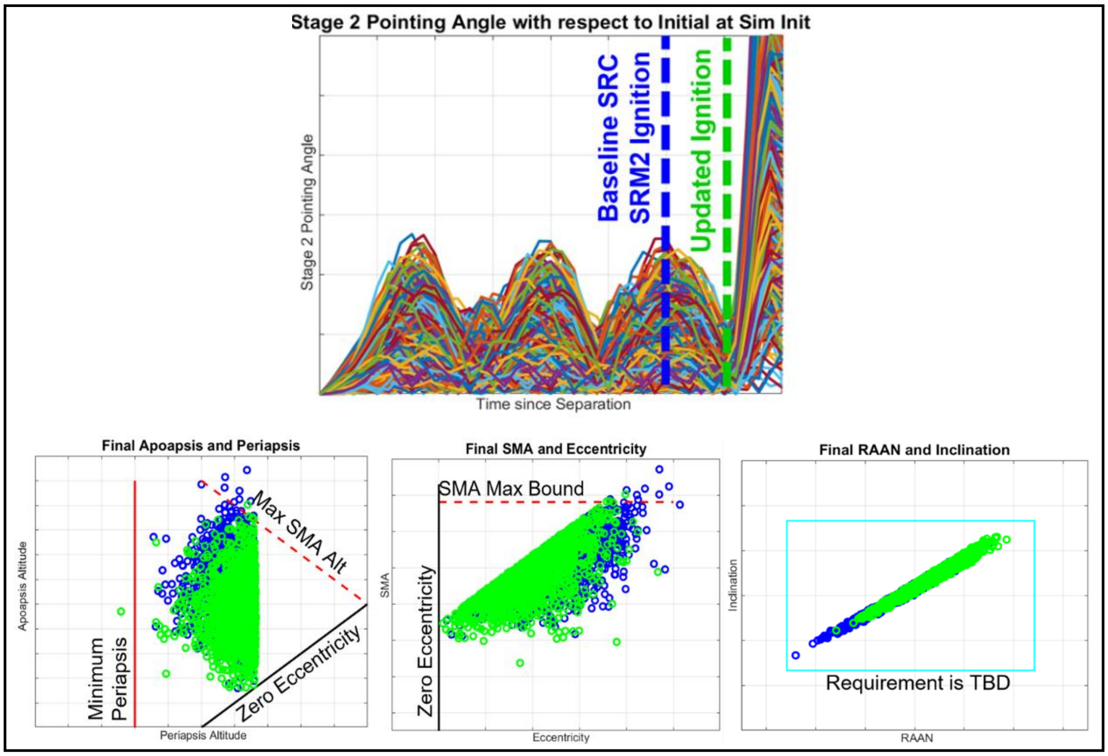

Figure 20. Timing of SRM2 burn relative to precessional pointing error (above) has a major impact on final Stage 2 orbit (below): low error burn (green), high error burn (blue).

The pointing error plot in Figure 20 demonstrates the importance of timing the SRM2 burn based on the Stage 2 precession. If the SRM2 burn is initiated at a peak in the precessional pointing error, the final orbital performance is substantially reduced. Therefore, the SRM2 must fire during a time when the pointing error is low. Fortunately, the precession of Stage 2 is determined in advance from the rotational inertias of the stage and the thrust of the Spin-Up Motors, so the proper burn timing can be determined in advance.

All of these sensitivities, and mitigations for these sensitivities, were identified using the CLVTOPS simulation. The simulation also was vitally important to developing mitigating strategizes and conducting hardware trades to improve the separation performance.

CONCLUSION

MAV Stage Separation is an important event to model and simulate accurately to ensure MSR mission success. Due to the high sensitivity of the unguided MAV Stage 2, the full range of possible disturbances caused by Stage Separation must be carefully assessed in terms of the final MAV payload orbit. The CLVTOPS toolchain provides a robust, capable, and flexible suite of tools which allows for high-fidelity analysis of multibody dynamical systems and has been essential in informing MAV design and confirming MAV performance as the configuration has evolved. By using the CLVTOPS toolchain, key sensitivities were identified for the Stage Separation event, and problem areas were mitigated by updating separation hardware and tuning system timing and performance. After extensive study of the MAV Stage Separation sensitivities and performance using several separation hardware designs and timing variations, a preliminary design was selected for use in the April 2023 Preliminary Design Review (PDR). The CLVTOPS toolchain will continue to be used as the design matures. By leveraging the advanced modeling and simulation capabilities at MSFC, the MAV team has taken great strides in the development of the first ever Mars-based launch vehicle.

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