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GN&C SEQUENCING FOR ORION RENDEZVOUS, PROXIMITY OPERATIONS, AND DOCKING

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As part of the Artemis program to return humans to the lunar surface, the National Aeronautics and Space Administration is planning to use the Orion Multi-Purpose Crew Vehicle to transport crew to a small orbital platform called Gateway in cislunar space. To facilitate this activity, Orion is required to perform Rendezvous, Proximity Operations, and Docking (RPOD) with both the Gateway and the launch vehicle upper stage.

The Orion spacecraft uses sequencing in the form of Phases, Segments, Activities, and Modes (PSAM) to configure Guidance, Navigation, & Control (GN&C) software during each portion of the mission. Significant updates to Orion PSAM definitions are required for RPOD. This paper describes the process of defining these new sequencing elements, implementing them in prototype flight software, and testing them in an integrated simulation environment.

First, requirements are specified to determine the nominal and off-nominal sequencing behavior necessary to complete the mission. These requirements also specify which software functions should be fully autonomous and which functions require manual interactions from crew or ground operators. Next, the RPOD concept of operations is defined with detailed events listed in a mission timeline. Third, a state machine diagram is developed to show all PSAM states, including all possible transitions between them. After this, the PSAM states and transitions are entered into a sequencing software emulator and parameter values and modes are defined for GN&C software elements. Finally, the PSAM architecture is tested within an integrated simulation environment by connecting it with prototypes of relevant GN&C flight software elements and with detailed vehicle models. After the sequencing design has been finalized and tested, it is implemented in flight software.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has started the Artemis program to land humans on the lunar surface by 2024. This initial mission will be followed by a series of human landings to establish sustainable human presence on the Moon. To accomplish this goal, NASA will launch crews of astronauts from Earth onboard the Orion spacecraft using the Space

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Launch System (SLS) rocket. Orion will then transport the crew from Low Earth Orbit (LEO) to cislunar space.

Prior to the arrival of the first human landing mission, components of an orbital platform called Gateway will be launched and assembled in a Near-Rectilinear Halo Orbit (NRHO) around the Moon[1]. A human lunar lander will also be launched and docked to the Gateway prior to Orion's arrival. Orion will conduct Rendezvous, Proximity Operations, and Docking (RPOD) with the Gateway, and the crew will move from Orion into the Gateway. When Gateway has reached the proper point in its orbit, crew members will board the lander and proceed to the lunar surface. After surface operations are complete, the crew will return to Gateway and board Orion, which will then undock and return to Earth. For some Artemis missions, Orion will also be required to perform Proximity Operations and Docking with the Exploration Upper Stage (EUS) of the SLS in order to extract a Comanifested Payload (CPL), such as a Gateway module, which Orion would then transport to the Gateway[2].

Orion is required to have the capability to perform RPOD both autonomously and manually. Although most RPOD functions will be autonomous, the crew of Orion will likely be involved in manual commanding and control during key portions of RPOD operations, including monitoring the automation. This paper focuses on the development of automated sequencing for Orion RPOD Guidance, Navigation, & Control (GN&C) software. For the purpose of this paper, it is assumed that all sequencing proceeds autonomously, but key points where manual interaction from crew or ground operators is expected during autonomous flight are specified. First, the Orion RPOD Concept of Operations (ConOps) is presented in detail. Next, the Orion GN&C sequencing architecture is explained and the RPOD-specific sequencing design described. Finally, the process for implementation and testing of RPOD sequencing is outlined.

ORION RPOD CONCEPT OF OPERATIONS

After transferring from the Earth to the Moon, Orion performs an Outbound Powered Flyby (OPF) burn near the Moon, which sets up an intercept with the NRHO in the vicinity of Gateway. Several Outbound Trajectory Correction (OTC) burns are performed to adjust the trajectory during this transfer. The NRHO Insertion (NRI) burn is performed to transition Orion from the transfer trajectory to the NRHO for RPOD operations. Orion remains in the NRHO docked to Gateway for just over one full revolution (9.5-11 days) before undocking and performing an NRHO Departure (NRD) burn.[1] Orion then performs a Return Powered Flyby (RPF) burn near the Moon to place it on a return trajectory to Earth. This sequence is shown in Figure 1.

The dynamics of rendezvous operations in an NRHO are quite different from rendezvous in LEO or other circular orbits. Rather than the typical cyclic behavior described by the Clohessy-Wiltshire equations, dynamics in an NRHO are very nearly linear. Some unique requirements also guided the trajectory design for Orion to dock with the Gateway. The RPOD trajectory must be passively safe, meaning that if any fault occurs that will prevent Orion from performing translational burns, the free-drift or coast trajectory should not intercept a 1 km Approach Sphere (AS) or a 200 m Keep-Out Sphere (KOS) around Gateway for 24 hours. The trajectory is only allowed to enter the AS or KOS after "Authority To Proceed" (ATP) is granted either by the crew or by ground operators. The free-drift trajectories before each burn are shown as dotted lines in Figures 2 through 4. The RPOD trajectory is represented in a Gateway-centered reference frame, as shown in Figure 2.

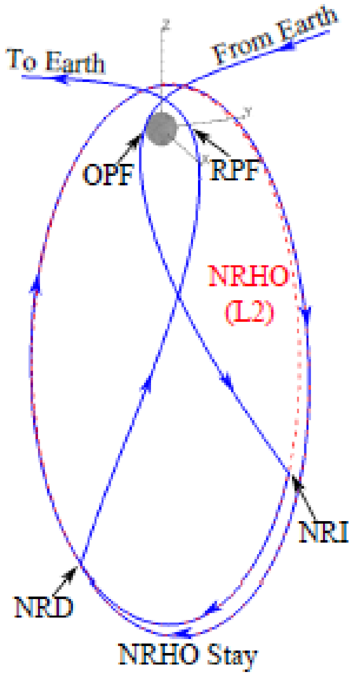

Figure 1. Orion intercept and departure trajectory with NRHO in Earth-Moon Rotating frame.[1]

The first portion of the RPOD trajectory is called "Far Range" and is shown in Figure 2. The NRI burn is performed at a range of several hundred kilometers from Gateway. The same point relative to Gateway is targeted for NRI, regardless of the launch date and orbital mechanics of Gateway relative to the Earth and Moon. This allows the RPOD approach trajectory to be standardized with minor modifications for multiple missions and launch dates. Prior to NRI, relative state estimation is derived by onboard state vector differencing between Orion and Gateway states and supplemented by relative sensor measurements if available. Post-NRI, relative sensor measurements are the primary source of navigation.[2]

NRI is followed by a series of Rendezvous Burns (RB), which are designed to reduce the relative velocity of Orion while maintaining passive safety. These burns are performed with Orion's Orbital Maneuvering Engine and Auxiliary engines using a "turn-to-burn" paradigm. An attitude maneuver is performed to point the thrust vector of the engines in the direction of the burn. During this time (~20-30 minutes, depending on burn duration), relative sensors will not be able to point toward Gateway. After the burn is complete, Orion rotates its nose toward Gateway again to resume acquisition of relative sensor measurements.

The Mid-Range portion of the RPOD trajectory begins after RB3 and is shown in Figure 3. After the completion of the RB3 burn, the AS constraint will be violated, meaning that an ATP is necessary before performing RB3. During Mid-Range RPOD, Orion stays on a path parallel to the docking axis for passive safety. Starting with RB4, all other burns until docking are completed as multi-axis burns using Orion's Service Module Reaction Control System (SM RCS) thrusters. During multi-axis SM RCS burns, the relative sensors can continue to track the target, because a "turn-to-burn" attitude maneuver is required. Mid-Range RPOD ends with the RB5 burn moving Orion off of the parallel path and toward the z-axis not.

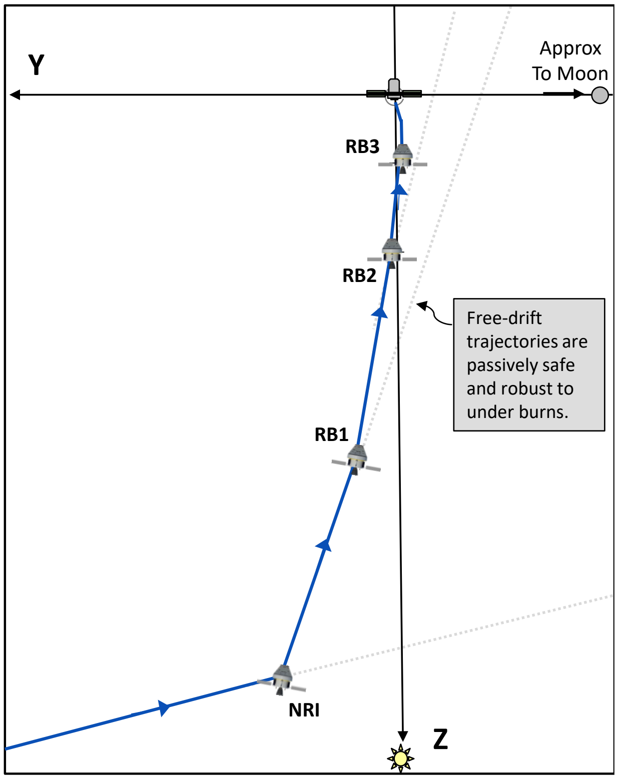

Figure 2. Far Range RPOD trajectory (not to scale).

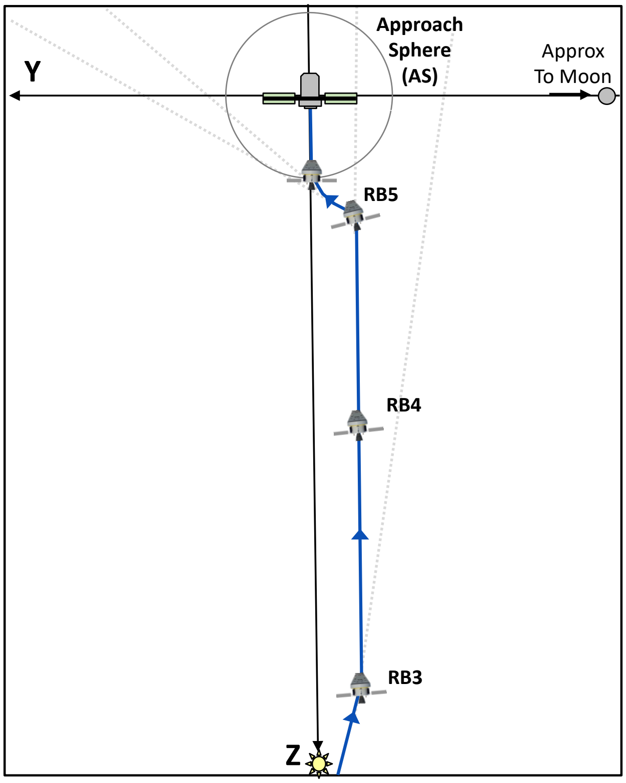

Figure 3. Mid-Range RPOD trajectory (not to scale).

The Close Range portion of the RPOD trajectory begins at the completion of the RB5 burn and continues until docking, as shown in Figure 4. RB5 is unique because during the burn the free-drift path of Orion passes through Gateway's KOS. Thus, if an underburn occurs there is a risk of collision with Gateway. After RB5, Orion performs maneuvers to ensure that Gateway will remain within the field of view of Orion's relative sensors during the transition to the docking axis. Unlike the previous burns, these corrections are not planned to occur at specific times but will be automatically commanded by the GN&C system on an as-needed basis.

When Orion reaches the z-axis, the RB6 burn is performed to place Orion on its approach to dock with Gateway. Because the free-drift trajectory will enter and stay in the KOS after the RB6 burn, an ATP is required prior to executing RB6. Following RB6, Orion passes through a series of range rate (braking) gates, which are small burns to decrease range rate at set intervals based on range to Gateway. Finally, at a range of several meters from Gateway, Orion performs a planned hold by zeroing its range rate and executing stationkeeping burns while aligning its docking port with Gateway's docking port. After a final ATP from the crew, Orion then moves forward to make contact and dock with Gateway.

When Orion is ready to depart from Gateway, it first releases the docking mechanism to push off from the docking port. Orion then passes through the range rate gates in reverse to increase its separation rate from Gateway at set intervals of range. When a range of several hundred meters is reached, Orion will perform an initial Departure Burn (DB1) using multi-axis SM RCS. Then, a series of Departure Burns will be performed, followed by NRD to depart from the NRHO. Unlike the approach burns, the timing, location, and engine used for each of these departure burns will be mission-specific and determined by the orbital mechanics of Gateway relative to the Earth and Moon. A notional departure sequence is shown in Figure 5.

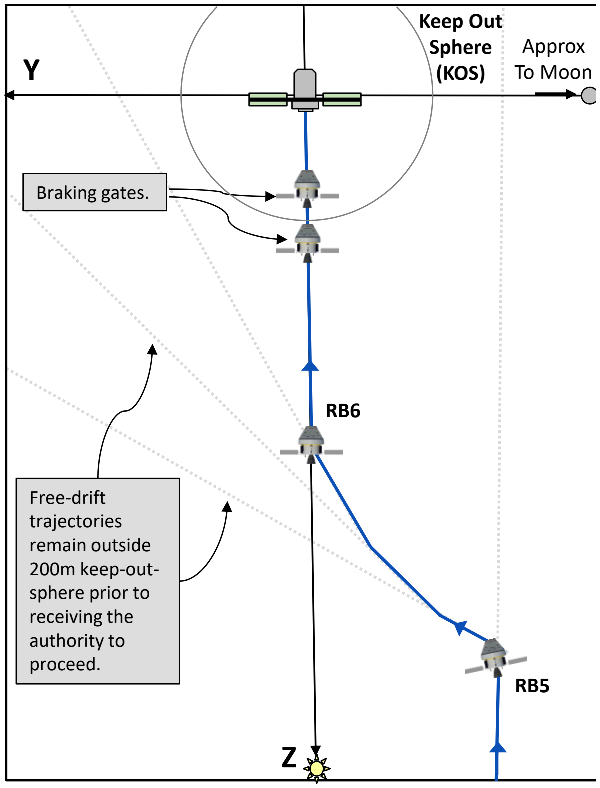

Figure 4. Close Range RPOD trajectory (not to scale).

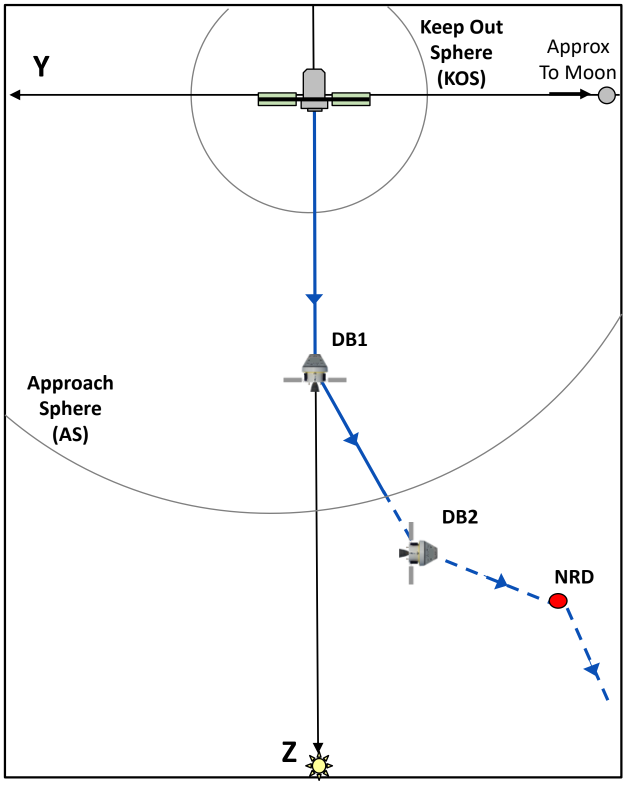

Figure 5. RPOD Departure trajectory (not to scale).

ORION RPOD SEQUENCING DESIGN

The Orion GN&C Flight Software (FSW) architecture is designed to operate highly autonomously. Artemis I, the first test flight of Orion in cislunar space is uncrewed and completely autonomous. Artemis II, the first crewed test flight of Orion, will include the capability for both autonomous and manual control by the crew. The mechanisms developed to handle sequencing for the autonomous GN&C FSW are called Phases, Segments, Activities and Modes (PSAM).[3] The PSAM sequencing architecture has been used extensively during the Artemis I and Artemis II missions. However, RPOD is not used until Artemis III.

Phases define major portions of the mission such as launch, low-Earth orbit, cislunar flight, and entry. Segments define subdivisions within each mission phase, such as coast, burn configuration, and burn execution within the cislunar flight segment. Segments also involve vehicle-wide reconfiguration and are handled by Timeline Management software rather than GN&C software. Activities are specific divisions within each segment that define discrete software configurations by specifying GN&C software parameter values and Modes. Modes define which GN&C software units in each GN&C software domain will run during a given activity. Parameter values fed as inputs to GN&C algorithms can also be changed at activity transition boundaries, allowing multiple parameter sets to be used for each Computer Software Unit (CSU) during different portions of the RPOD trajectory. Figure 6 illustrates the hierarchy of PSAM sequencing elements within the Orion mission timeline. Transitions between Phases, Segments, and Activities are datadriven and can include conditions based on hardware states, software states, and vehicle dynamic states.

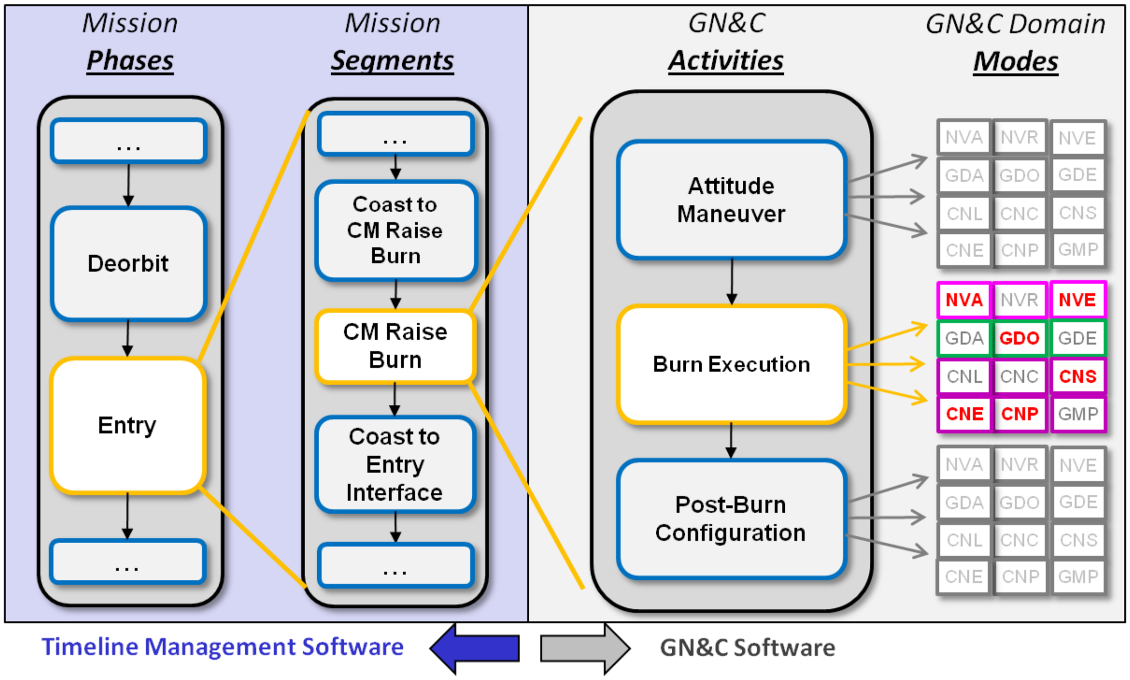

Figure 6. Illustration of Orion GN&C sequencing Phases, Segments, Activities and Modes (PSAM).[3]

The nominal Orion RPOD trajectory design and ConOps described in the previous section were developed based on simulations with prototype GN&C algorithms. However, in order to implement these new operations within the Orion GN&C FSW, an extensive new set of PSAM sequencing is required. This includes the addition of a new RPOD mission phase with multiple new segments and dozens of new activities. Several goals were stated as the design of RPOD PSAM sequencing began: to re-use as much of the Artemis I and Artemis II sequencing as possible, to develop common RPOD Phases and Segments to support all future mission operations, and to keep the sequencing agnostic to trajectory design where possible.

The first step in sequencing design was for the RPOD GN&C team to meet together and discuss every step of the RPOD ConOps in detail. The name, contents, and transitions between each RPOD event relevant to the GN&C software were recorded in a spreadsheet to document them for common reference. Next, a nested state machine diagram was developed to describe the Phases, Segments, and Activities relevant to RPOD. It was decided that rather than extending an existing mission Phase, a new Phase should be created called *RPODOperations*. This was done to reduce confusion from altering existing Artemis I/II sequencing and to minimize the amount of sequencing re-verification necessary.

Transitions into and out of the *RPODOperations* Phase are shown in Figure 7. If Orion needs to perform RPOD with the EUS to extract a CPL, then FSW will transition the mission phase from *EarthOrbitOps* to *RPODOperations* immediately after separation of Orion from EUS. Proximity Operations, Docking, and CPL extraction from EUS all occur in *RPODOperations*. Then after Orion departs from EUS, FSW transitions into *ExoLEOOperations* for transfer from Earth to the Moon. If no RPOD operations with EUS are required, *EarthOrbitOps* transitions directly to *ExoLEOOperations* (the default behavior for Artemis I and II). Existing *ExoLEOOperations* sequencing will be used for all translational burns prior to NRI. When the range to Gateway drops below a parameterized value, FSW will transition from *ExoLEOOperations* into *RPODOperations*. The exact range for this transition is To Be Determined (TBD), but it will be somewhat larger than the maximum expected range that Orion's relative sensors can obtain measurements of the relative position to Gateway (several hundred kilometers). If this range is not reached by one hour before NRI, the transition will occur anyway. After Orion departs from Gateway and leaves the NRHO, the phase will transition back to *ExoLEOOperations* for transfer back to Earth.

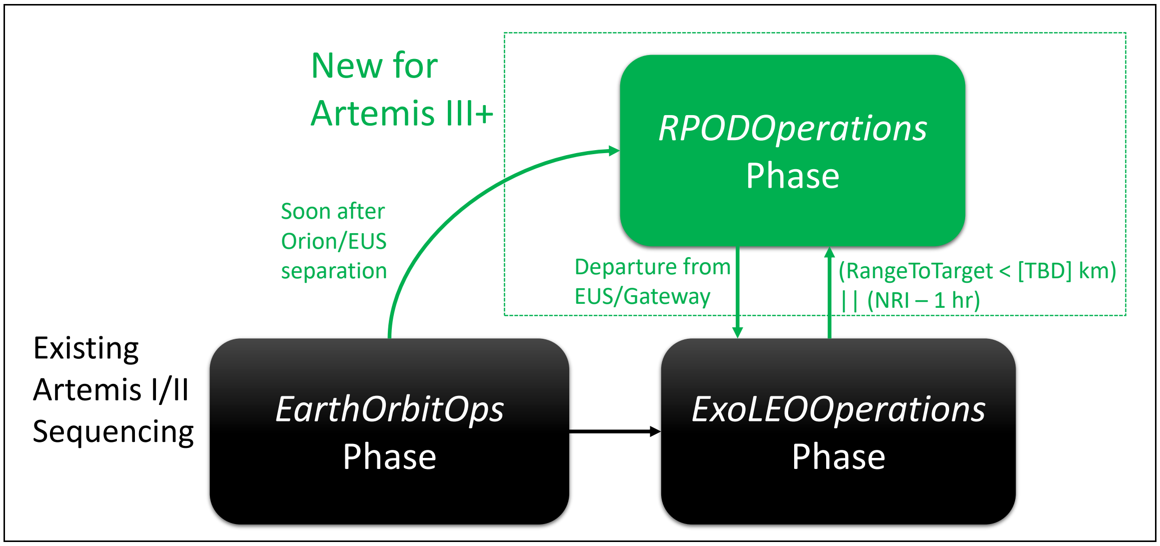

Figure 7. State machine diagram showing transitions to and from the *RPODOperations* Phase.

Segments within the *RPODOperations* phase were designed using the Far, Mid, and Close Range divisions described in the previous section. Figure 8 shows the nominal RPOD Segments and transitions between them. Three segments are used to execute the Far Range portion of the RPOD trajectory, where all burns use the "turn to burn" paradigm. During the *RPOD_Coast* Segment, Orion tracks Gateway with its relative sensors and runs initial burn targeting and guidance algorithms. Then, 20 minutes before the planned Time of Ignition (TIG) for a Far Range burn, FSW transitions into the *RPOD_Burn_Config* Segment, which rotates Orion to the burn attitude and positions solar arrays for the burn. Finally, at 5 minutes before TIG, FSW transitions into the *RPOD_Burn* Segment for execution of the burn and evaluation of failures before, during, and after the burn. After the burn and any subsequent trim are complete, FSW returns to the *RPOD_Coast* segment. This cycle repeats for each Far Range burn. This sequencing is based on the paradigm designed for Artemis I, but with modifications to allow for relative operations.[4,5]

The transition from the *RPOD_Coast* Segment (Far Range) into the *RPOD_Mid_Range* Segment occurs after the final "turn to burn" (currently RB3) is complete. All burns during *RPOD_Mid_Range* use multi-axis SM RCS and have discrete, pre-defined TIGs. As with the Far Range burns, there is some cyclic re-use of sequencing for the Mid-Range burns, but only one Segment is used instead of three because fewer vehicle and GN&C software reconfigurations are needed for multi-axis SM RCS burns.

After RB5 is complete, FSW transitions into the *RPOD_Close_Range* Segment. Close Range burns are not defined by discrete TIGs; they are either correction burns commanded as-needed or are triggered based on range rather than time. Also, for an EUS docking and CPL extraction, FSW transitions directly into *RPOD_Close_Range*, from the *EarthOrbitOps* Phase, bypassing the

Far and Mid-Range segments. The sequencing for final approach and capture is re-used for both the EUS docking and the Gateway docking. The transition from *RPOD_Close_Range* Segment to the *Docked* Segment occurs at the end of docking when hard capture is complete and an airtight structural seal is established between Orion and Gateway. FSW remains in the *Docked* Segment until an undocking command is given by the crew, triggering a transition back into *RPOD_Close_Range*.

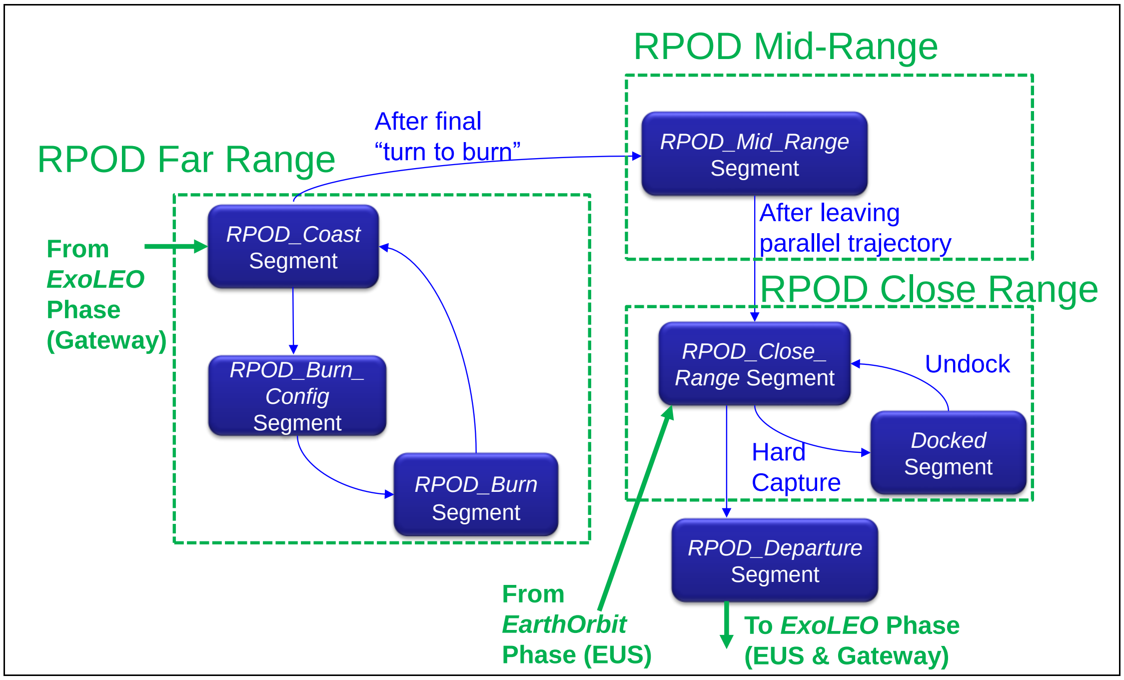

Figure 8. State machine diagram showing nominal RPOD segments and transitions.

For departure from Gateway, FSW remains in the *RPOD_Close_Range* Segment while backing away from Gateway and performing any additional Close Range maneuvers such as a fly around inspection. Before departing from EUS or Gateway, FSW transitions to the *RPOD_Departure* Segment and performs the departure burn, For departure from EUS, FSW transitions directly to the *ExoLEOOperations* Phase, and for departure from Gateway, FSW transitions into the *RPOD_Coast* Segment to execute a mission-specific set of departure burns and then NRD before returning to *ExoLEOOperations*.

In each of the Segments described above, detailed Activities are defined to specify the behavior of the GN&C FSW from event to event. State machine diagrams are created using the Stateflow toolbox in MATLAB/Simulink to illustrate the sequencing. These diagrams serve as documentation of the RPOD sequencing design, though they do not translate directly to FSW code. The diagram showing all RPOD activities is too large and complex to reproduce here, but a small portion of the diagram is included in Figure 9. The particular group of activities in Figure 9 shows the events from final approach through docking and then the undocking and separation sequence. The RPOD GN&C team has discussed in detail the desired GN&C software behavior during each Activity, which is then translated into GN&C Modes.

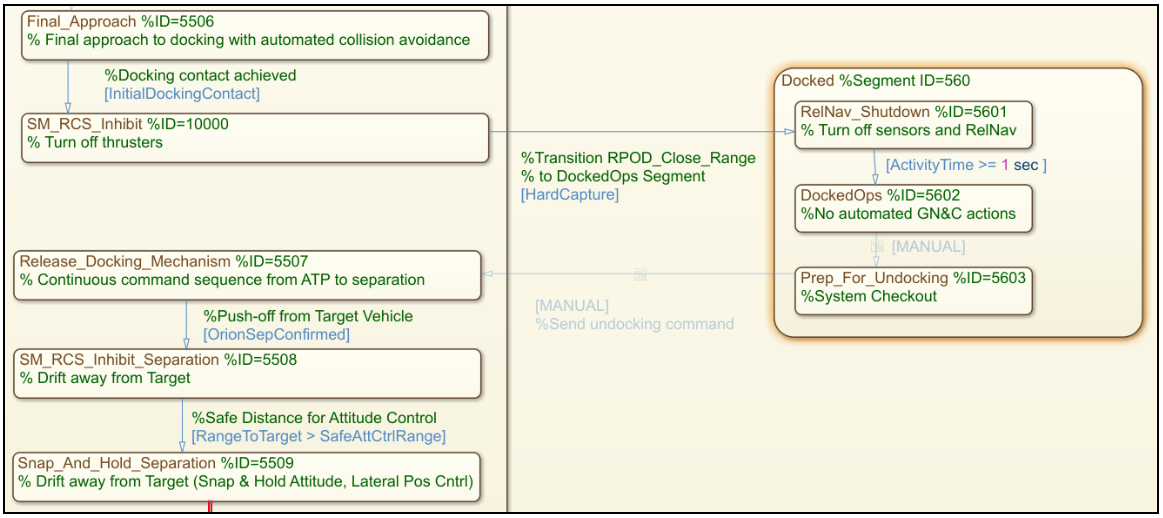

Figure 9. Example state machine diagram showing how RPOD activities are documented.

All of the sequencing described so far in this section has been for nominal RPOD ConOps. Off-nominal trajectory design is currently underway and has not been finalized. However, possible off-nominal paths have been established for Gateway RPOD. At any point prior to RB6, Orion can perform a passive flyby simply by stopping all commands to execute burns. This involves a transition to an *RPOD_Passive_Flyby* Segment. Also, during most portions of the RPOD trajectory, a position hold and/or retreat can be commanded to pause the approach sequence and resume within a few hours. This is achieved by transitioning into one of three Segments: *RPOD_Far_Range_Hold_Retreat*, *RPOD_Mid_Range_Hold_Retreat*, or *RPOD_Close_Range_Hold_Retreat*. The RPOD approach can be aborted temporarily, allowing the crew to stop the RPOD sequence, perform a “safing” burn to set up for long-term troubleshooting, and resume the approach on the next crew day. Finally, the crew can abort the approach permanently and immediately depart from Gateway. These aborts are commanded by transitioning into *RPOD_Far_Range_Abort*, *RPOD_Mid_Range_Abort*, or *RPOD_Close_Range_Abort* Segments. Of the scenarios listed here for Gateway, only short-term hold/retreat and abort followed by immediate departure are possible while performing RPOD with EUS. Currently, it is expected that transitions into any of the off-nominal RPOD Segments will be manually commanded by the crew, not triggered autonomously by on-board fault detection logic. The notable exception to this is automated collision avoidance maneuvers at very close range to Gateway and EUS. A Caution & Warning display to provide information about fault status to the crew and allow them to decide if a manual transition command is necessary. This display will show outputs from fault detection logic and active trajectory monitoring algorithms.

ORION RPOD SEQUENCING IMPLEMENTATION

After completion of the sequencing design process described in the previous section, the RPOD sequencing is first implemented in simulation for testing with GN&C FSW algorithms. The Orion GN&C FSW is developed in MATLAB/Simulink using a tool called the Rapid Algorithm MATLAB Simulink Engineering Simulation (RAMSES).[6] Information about Phases, Segments, and Activities from the state machine diagrams described in the previous section are entered into the PSAM Database Configuration Tool (also known as the PSAM tool) within the RAMSES environment.[3] This includes defining exactly which data parameters within the FSW will be used to evaluate transition conditions between Segments and Activities. The specific input parameter values for each CSU and the Mode for each GN&C FSW domain are specified within each Activity in the PSAM tool. The RAMSES environment is then used for extensive software development and testing, using the PSAM data entered into the PSAM tool. For RPOD, the RAMSES environment is also used to perform human-in-the-loop simulations to evaluate GN&C algorithm performance.

It should be noted that unlike the CSUs, PSAM sequencing information is not autocoded from the PSAM tool directly into FSW but is rather entered manually by FSW developers into the Rhapsody environment within Timeline Vehicle Management software (for Phases and Segments) and GN&C Executive software (for Activities and Modes). When all GN&C CSUs and PSAM information have been integrated with the rest of FSW in Rhapsody, source code is generated and tested for formal verification & validation, through both software simulation and hardware-in-the-loop testing.

CONCLUSIONS

This paper presented the Orion RPOD concept of operations, GN&C sequencing design, and implementation process. The RPOD sequencing capability builds upon existing Orion GN&C sequencing design and expands it for the added challenges of Rendezvous, Proximity Operations, and Docking. The design of the RPOD sequencing is intended to allow flexible operations and accounts for both nominal and off-nominal scenarios, including the challenge of mixing between autonomous and manual control.

ACKNOWLEDGMENTS

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