

Onboard Autonomous Trajectory Planning for Mars Power Descent

Pardha Sai Chadalavada*

Analytical Mechanics Associates, Hampton, VA 23681, USA

Justin S. Green*, R. Anthony Williams*, Soumyo Dutta†

NASA Langley Research Center, Hampton, VA 23681, USA

In recent years, there has been an increasing interest in space-qualified processors such as multi-core central processing units and graphics processing units that can withstand the adverse effects of space radiation. These processors can allow parallel programming to perform tasks that typically demand high computational power. One can study guidance schemes that can take advantage of these currently developing processors and provide more robust guidance. Software for Multi-model Autonomous Real-time Trajectories (SMART) guidance can identify robust trajectories by running an onboard Monte Carlo analysis. SMART guidance can take advantage of knowledge updates obtained from the onboard sensors, allowing it to consider the off-nominal cases that it would not typically encounter during the offline trajectory analysis. This work uses the SMART guidance for the powered divert at Mars simulation in Program to Optimize and Simulated Trajectories- II.

I. Nomenclature

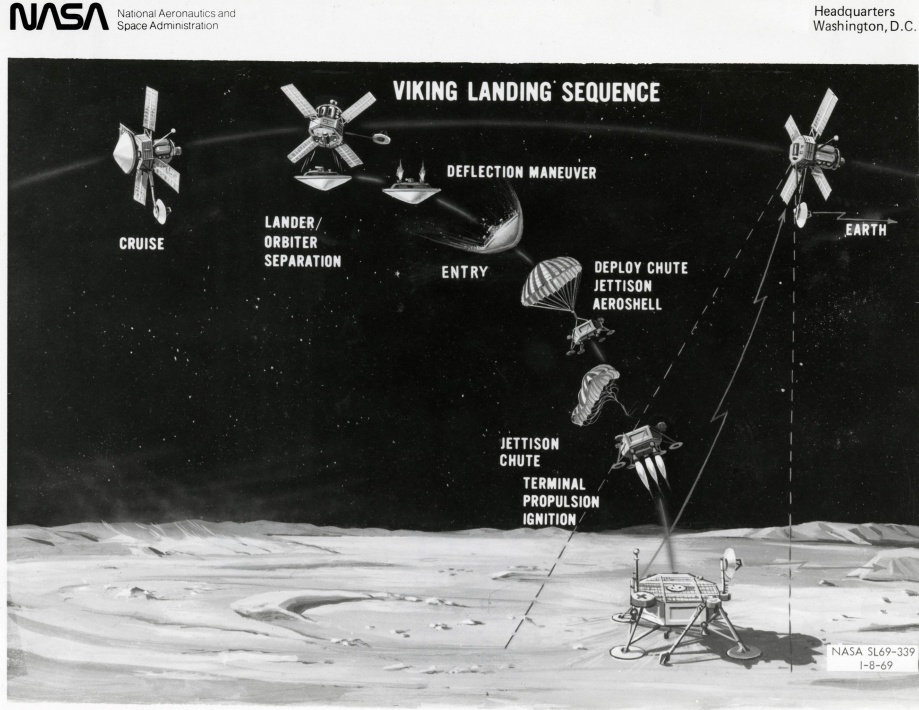
SMART	=	Software for Multi-model Autonomous Real-time Trajectories
EDL	=	Entry, Descent, and Landing
POST2	=	Program to Optimize and Simulated Trajectories- II
MFMC	=	Multi-Fidelity Monte Carlos
6DOF	=	Six Degree Of Freedom
PID	=	Proportional-Integral-Derivative
MLE	=	Main Lander Engine
UQ	=	Uncertainty Quantification
GNC	=	Guidance, Navigation, and Control
IMU	=	Inertial Measurement Unit
X-J2000	=	x-component of the inertial position vector in J2000 frame coordinates
Y-J2000	=	y-component of the inertial position vector in J2000 frame coordinates
Z-J2000	=	z-component of the inertial position vector in J2000 frame coordinates
VX-J2000	=	x-component of the inertial velocity vector in J2000 frame coordinates
VY-J2000	=	y-component of the inertial velocity vector in J2000 frame coordinates
VZ-J2000	=	z-component of the inertial velocity vector in J2000 frame coordinates
Q_I2B_0	=	first element of the quaternion describing the attitude from inertial frame to body frame
Q_I2B_1	=	second element of the quaternion describing the attitude from inertial frame to body frame
Q_I2B_2	=	third element of the quaternion describing the attitude from inertial frame to body frame
Q_I2B_3	=	fourth element of the quaternion describing the attitude from inertial frame to body frame

II. Introduction

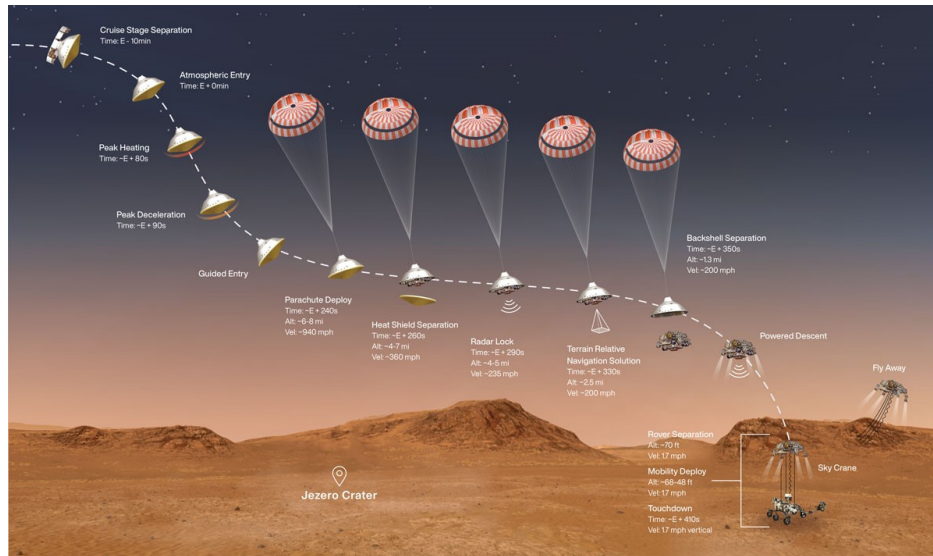
IN recent decades, science missions to several planets and their moons, such as Mars 2020 [2], Mars Science Laboratory [3], and Cassini-Huygens [4] have been launched. In addition, many more missions, such as Mars sample

* Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, AIAA Member.

† Aerospace Engineer, Atmospheric Flight and Entry Systems Branch, AIAA Associate Fellow.



(a) EDL Sequence for Viking in 1976 [1]



(b) Perseverance Rover's EDL Sequence [1]

Fig. 1 Evolution of EDL Mission at Mars

return mission [5] and Dragonfly [6], are currently in development. In addition to robotic missions in the near future, human exploration missions to Mars are gaining a lot of interest [7]. To this end, the Entry, Descent, and Landing (EDL) of aerospace vehicles has been studied significantly in the literature. The EDL sequence has matured with technological development and lessons learned from past missions. Figure 1 compares Mars EDL's rather benign Viking lander sequence in 1976 and the more complicated Perseverance rover sequence in 2020. More advanced missions, such as human exploration missions and sample return missions, will be required to have the capability of a pinpoint landing to satisfy the mission requirements, such as landing close to on-ground assets. Missions would need to determine robust

guidance for safe and efficient powered divert trajectories that can enable the pinpoint landing for these advanced space missions. There are several guidance schemes in literature developed for the powered divert phase of the EDL missions such as polynomial guidance [8], predictor-corrector guidance [9], and Guidance FOr Large Diverts (G-FOLD) [10].

Extensive offline trajectory analysis is required to determine the nominal guidance for EDL missions, including those using the powered divert guidance, such as the previous Mars missions [11]. For this analysis, several uncertainties such as atmospheric, aerodynamic, navigation, and mass properties, are modeled conservatively to account for the errors in the engineering models. However, such guidance schemes are only robust to the uncertainties modeled during the trajectory analysis. If the vehicle encounters unanticipated conditions (e.g., large off-nominal atmospheric perturbations), the predetermined guidance will sometimes result in performance loss or failure of the mission. Human-in-the-loop interference is impractical for these precision landing applications on distant planets, as the one-way light time is on the order of minutes, and typically, EDL missions are on the order of tens of minutes. To this end, the vehicle has to be capable of making onboard autonomous decisions to land safely and efficiently.

Typically, EDL vehicles are equipped with sensors such as Inertial Measurement Unit (IMU), Terrain Relative Navigation (TRN), and Altimeter, among others, that collect data in real time. These sensors can then aggregate that sensed data into measured conditions with smaller uncertainties [12, 13]. One can leverage this data, which is unavailable during the offline trajectory analysis, to determine more accurate, robust, and efficient powered divert guidance. To do so, the vehicle has to be capable of determining the guidance in real time by performing similar tasks as offline methods, such as analyzing the Monte Carlo analysis. Using the onboard sensor data will help to better estimate the uncertainties and avoid over-conservatism in modeling uncertainties that would otherwise be done during the offline analysis. However, performing a Monte Carlo analysis onboard the vehicle can be computationally expensive.

In recent years, the development of radiation-hardened processors for space missions has paved the way for onboard parallel programming [14–16]. This advancement has enabled the practical application of the Software for Multi-model Autonomous Real-time Trajectories (SMART) guidance [17]. SMART guidance, determined through a Monte Carlo analysis that uses sensor data to characterize uncertainties, can autonomously generate robust and safe trajectories. This capability is particularly essential for practical applications like powered divert maneuvers. This study demonstrates the practical application of SMART guidance in simulating a powered divert at Mars within the Program to Optimize and Simulated Trajectories- II (POST2) [18].

The rest of the paper is organized as follows: Section III discusses the SMART guidance and POST2 simulation setup in detail. The numerical simulations of the Mars-powered divert in POST2 using the SMART guidance are presented in Section IV. Finally, the conclusions of this study are presented in Section V.

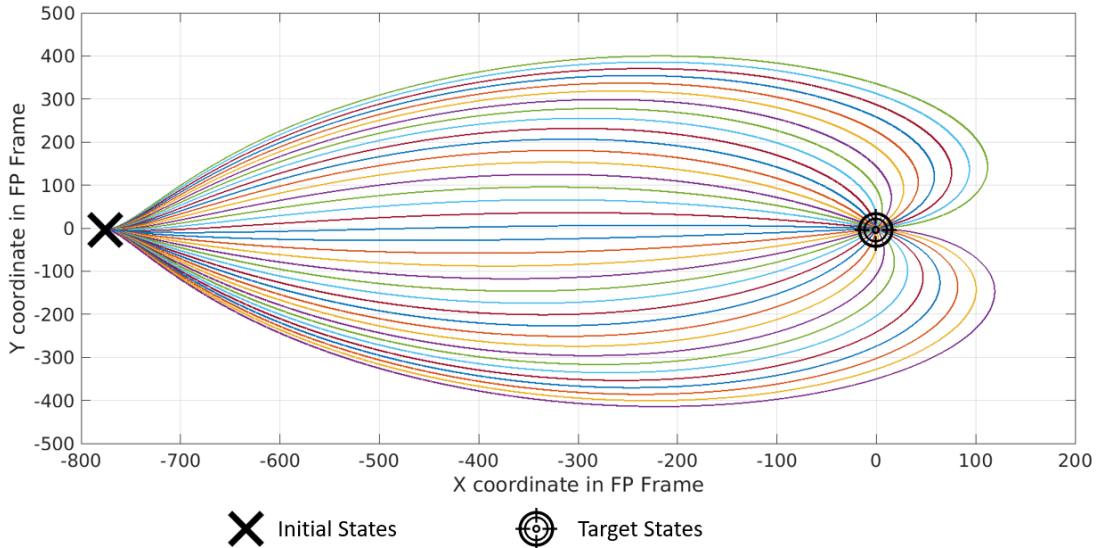


Fig. 2 N Trajectories with different target azimuth considered by the SMART guidance

III. Simulation Setup

This section will discuss the SMART guidance and the models used to simulate the powered divert at Mars in POST2. This section will also discuss the POST2 - SMART guidance interface.

A. SMART Guidance

The SMART guidance is initialized with current states from the onboard navigation filter and considers an N number of candidate trajectories. The initial and target states remain constant for each of these N trajectories. However, the SMART guidance generates these N trajectories by considering different target approach azimuth angles as shown in Figure 2. For each trajectory, the SMART guidance integrates six degree of freedom (6DOF) equations of motion with open-loop polynomial guidance and closed-loop translational and quaternion Proportional-Integral-Derivative (PID) controllers. In addition, the SMART guidance also considers the thrust allocator that determines the Main Lander Engines (MLEs) throttle commands given their location on the vehicle and their thrust pointing directions to track the PID controller commands. Using these N -simulated trajectories, the SMART guidance eliminates possible trajectories based on specific metrics, such as passing through known obstacles characterized as no-go zones. The SMART guidance then evaluates each trajectory still being considered by defined scoring criteria and chooses a user-defined K number of top candidate trajectories. The metrics used for eliminating and scoring the trajectories are discussed in detail in Ref [19].

After determining the top K candidates from the original number of N trajectories, SMART guidance runs a Monte Carlo analysis for each of the K trajectories using parallel computing. The SMART guidance integrates the 6DOF equations of motion for the Monte Carlo analysis using the identical subsystems discussed earlier. However, for the Monte Carlo analysis the SMART guidance disperses the initial states and other parameters such as atmospheric properties, aerodynamic coefficients, and mass properties. The onboard navigation filter that can ingest sensor data provides various parameters' mean and standard deviation, such as the vehicle's current position, atmospheric states, and aerodynamic coefficients. The SMART guidance uses this onboard navigation filter data to characterize the uncertainties and use this information to perform onboard Uncertainty Quantification (UQ) analysis.

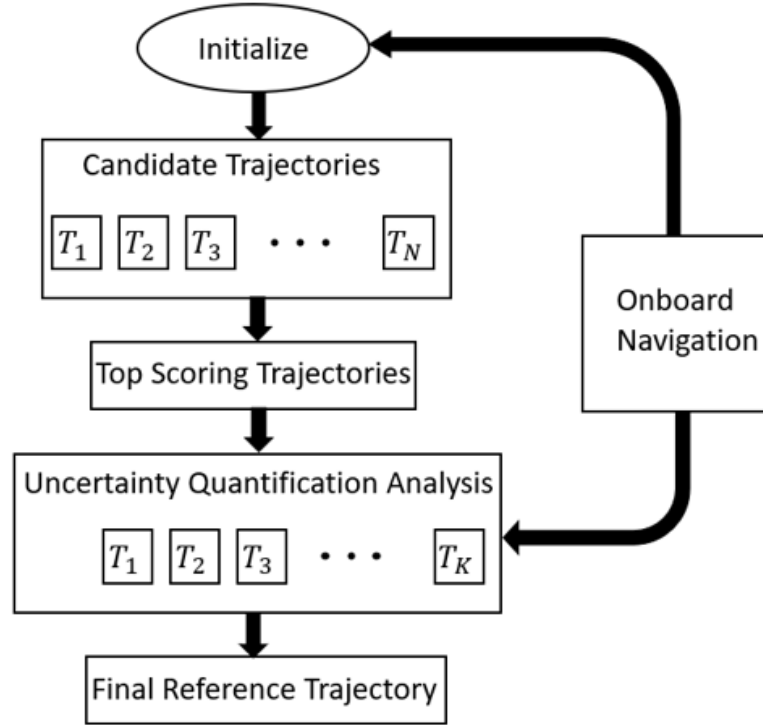


Fig. 3 High-level SMART Guidance Flow Chart

Performing Monte Carlo analysis for uncertainty quantification onboard the vehicle can be computationally expensive,

considering the limited onboard resources. Furthermore, this analysis has to be fast to enable the SMART guidance to compute the reference trajectory. In addition to the traditional Monte Carlo runs, the SMART guidance can run MFMC analysis. MFMCs leverage lower-fidelity models, specifically trajectory simulations with decreased time resolution analysis, to reduce the onboard computational effort. MFMC combines a few high-fidelity model simulations with many low-fidelity simulations. Combined, these provide relatively high statistical accuracy with relatively low computational effort [20]. However, this work uses traditional Monte Carlos analysis as it focuses mainly on integrating the SMART guidance with other simulation frameworks. Figure 3 shows the high-level SMART guidance flow chart with N number of candidate trajectories and K number of top candidates for whom SMART guidance will run Monte Carlo analysis. Finally, using the UQ analysis, SMART guidance chooses the most robust trajectory among the initially picked top candidates. During the Monte Carlo analysis, the SMART guidance considers specific elimination and scoring metrics to select the most robust and feasible trajectory that is similar to the nominal trajectories. It is important to note that these metrics can be user-defined and tailored to specific mission requirements. After choosing the final reference trajectory, the SMART guidance provides the commands from the polynomial guidance corresponding to the selected trajectory. One can call the SMART guidance once and use the guidance commands as an open-loop or call the SMART guidance at fixed intervals to have a closed-loop guidance system.

The SMART guidance uses two coordinate systems and frames: Flat Planet (FP) coordinate system and frame and Carried Flat Planet (CFP) coordinate system and frame. The FP frame has its origin at the target location and has a positive x-direction tangent to the curve joining the vehicle and the target with an azimuth of ψ_{Target} from north measured clockwise as shown in Figure 4. The positive z-direction of the FP frame is into the ground toward the planet's center. The positive y-direction of the FP frame completes the right-hand rule. The guidance computes all the reference trajectories in the FP coordinates system and frame. The CFP frame has its origin at the center of gravity of the vehicle. The positive x-direction of the CFP frame is also tangent to the curve joining the vehicle and the target, but with an azimuth of ψ_{Veh} from north measured clockwise as shown in Figure 4. Similar to the FP, the CFP frame has its positive z-direction into the ground towards the planet's center, and the positive y-direction completes the right-hand rule. The guidance acceleration commands computed in the FP frame are converted into the CFP frame before determining the vehicle attitude commands, such as desired pitch and yaw angles.

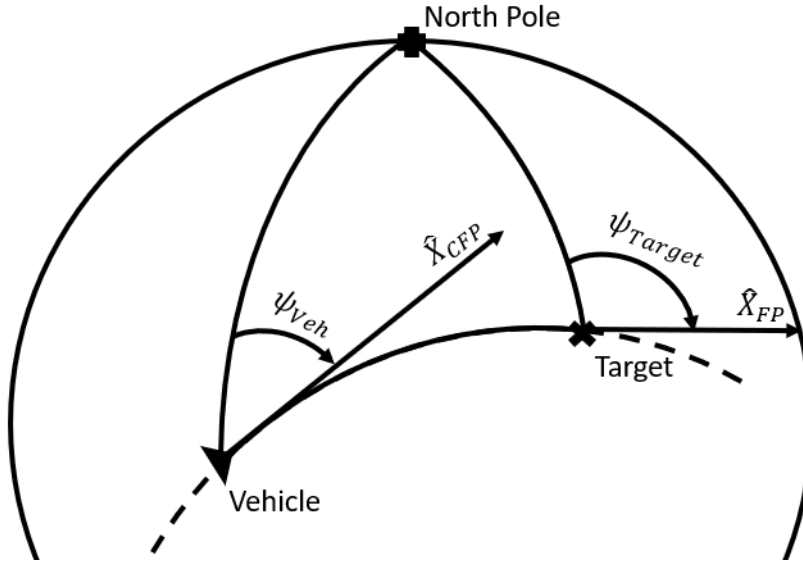


Fig. 4 Flat Planet (FP) and Carried Flat Planet (CFP) coordinate system and frame

B. POST2

Using the SMART guidance, the powered divert at Mars is simulated in POST2 for this study. POST2 is a generalized point mass, discrete parameter targeting, and optimization program. POST2 was developed leveraging the POST, whose development began in the 1970s. Over the years, POST2 has gone through significant improvements. POST2 is modular and allows for models such as atmosphere, gravity, propulsion, aerodynamics, and Guidance, Navigation, and Control

(GNC) to be integrated into a single simulation framework for various launch, orbital, and EDL missions. POST2 allows for both 3DOF and 6DOF simulations. Several past missions such as Mars Pathfinder [21], Mars Exploration Rovers [22], Mars Phoenix [23], Mars Science Laboratory [24], Mars InSight [25], and Mars 2020 (M2020) [26] utilized POST2 as its primary simulation tool, contributing to the flight heritage of POST2.

Figure 5 presents the POST2 simulation setup used in this work to simulate the powered divert at Mars. As mentioned earlier, the POST2 integrates several models as shown in Figure 5. Given the initial states, POST2 integrates the 6DOF equations of motions with external forces computed using models such as atmosphere, aerodynamics, and propulsion. POST2 also includes the vehicle configuration information that provides the mass properties and information such as engine locations and thrust pointing vectors. The terrain model containing a digital elevation map in POST2 is used to determine the height above the ground with respect to the planet's terrain. Using the current states and the uncertainties from POST2, SMART guidance computes the top candidate trajectory, as discussed earlier. The SMART guidance provides the required axial thrust, pitch, and yaw commands to the translational and quaternion controller. In addition to the guidance commands, the controllers will use the current vehicle states to compute the desired angular and translation accelerations. These desired accelerations are passed on to the thrust allocator model, which also has the vehicle configuration information. Given the desired accelerations, the thrust allocator determines the required throttle commands for each engine. The propulsion module in POST2 converts these throttle commands to propulsion forces and passes them on for the integration of the 6DOF dynamics of the vehicle. As discussed earlier, the POST2 states and uncertainties are passed to SMART guidance during every guidance call, which can be once or at regular intervals. The interface between POST2 and SMART guidance is a crucial component that ensures the seamless transfer of information and is discussed in detail in the following section.

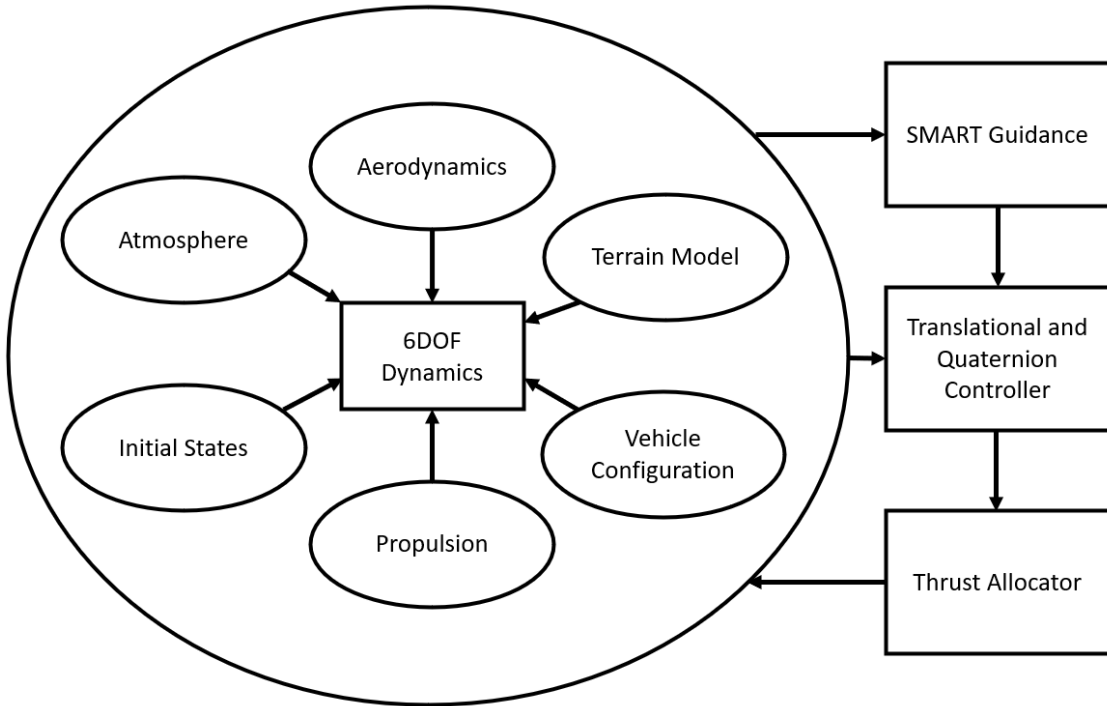


Fig. 5 POST2 Simulation Setup

C. POST2 - SMART Guidance Interface

This section will discuss the POST2 interface that passes the required information to the SMART guidance. As discussed earlier, the SMART guidance will simulate several trajectories and perform the Monte Carlo analysis within the guidance module. The SMART guidance will require information for different models (e.g., atmosphere, aerodynamics, and propulsion) within the guidance module to perform these simulations. To this end, the POST2-SMART guidance interface is called with every guidance call. This interface will pass the vehicle's current position, velocity, and attitude

to SMART guidance, which will be used as the initial conditions for the internal simulations. In addition, the vehicle will pass vehicle configuration information such as the center of mass location, vehicle inertia distribution, engine location on the vehicle body, and the thrust point vectors. This interface will also pass the target location states and no-go zone site information. Furthermore, this interface will also provide the SMART guidance with information regarding the vehicle's atmosphere and aerodynamics. The initial states, atmospheric, and aerodynamic properties passed to SMART guidance can be from the onboard filter, which will be better estimated as these are updated using the onboard sensor data gathered until the powered divert initialization. As the SMART guidance also runs the Monte Carlo analysis for the top candidate trajectories, the interface must pass the uncertainty in the states and other parameters (e.g., atmospheric properties) to the guidance. Typically, this information can also be estimated from the error covariance from the onboard filter.

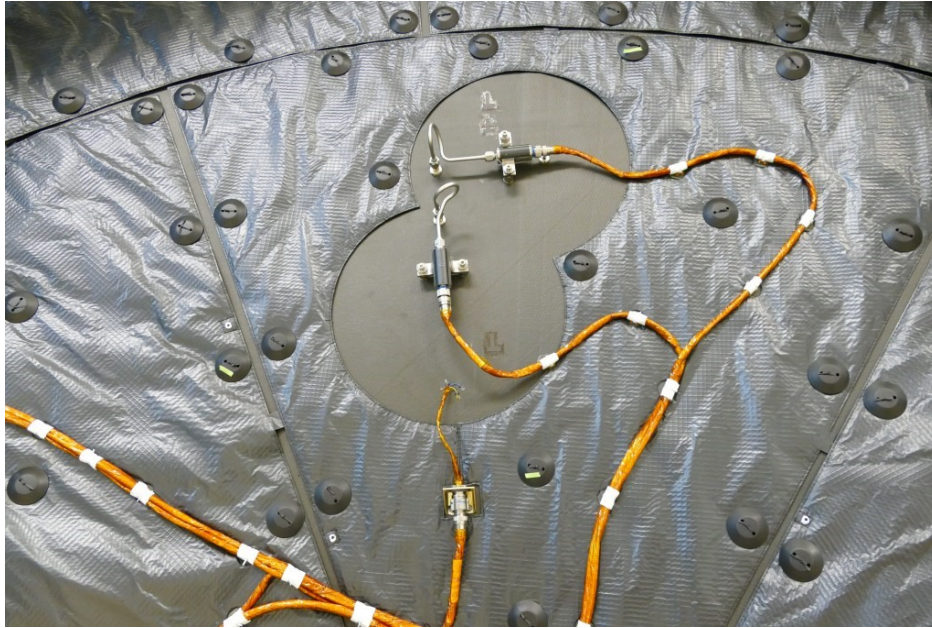


Fig. 6 MEDLI2 pressure transducers [27]

In this work, the onboard navigation filter and the other sensors in POST2 are not explicitly modeled. This work uses the Mars 2020 trajectory reconstruction data to initialize the powered divert simulation. In a recent study [28], M2020 trajectory and atmospheric reconstruction were done using onboard IMU and navigation sensor data. This reconstruction also considers data from Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2). MEDLI2 has several sensors such as pressure transducers which allow estimates of free stream atmospheric properties (as shown in Figure 6), thermocouples, heat flux gauges, and radiometers to measure the aerodynamic and aerothermodynamic performance [28]. Assuming the onboard navigation filter ingests all these sensor data and performs the same analysis during the reconstruction, the reconstruction data will be synergistic with the onboard navigation data and can be used to initialize the SMART guidance. To initialize the POST2 and SMART guidance using the trajectory reconstruction data, the nominal data and the standard deviation representing the uncertainty in the states are needed. These can be used for the Monte Carlo runs within the SMART guidance. The uncertainty computed using the error covariance from the reconstruction data is assumed to have a normal distribution.

IV. Numerical Simulations

This section shows the numerical simulation results of the Mars-powered divert in POST2 using SMART guidance. As discussed earlier, in addition to the outer loop simulation by POST2, SMART guidance also internally runs several nominal trajectories. This section presents the initial states, their corresponding uncertainties, and the target states from the M2020 reconstruction completed using the MEDLI2 data. This section briefly discusses the vehicle configuration. In addition, this section presents some of the nominal trajectories and the top candidates chosen by the SMART guidance after running the Monte Carlo analysis. Finally, the performance of the Mars-powered divert trajectory from POST2 is

analyzed.

Table 1 Target landing site from M2020

Parameter	Value
Latitude	18.4446 deg
Longitude	77.4508 deg
Elevation	-2569.91 m

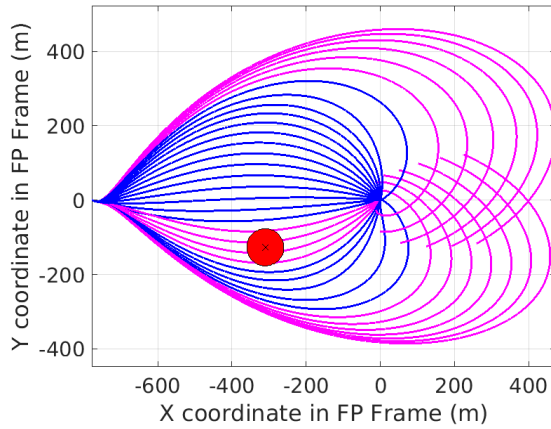
Table 2 Initial states and corresponding uncertainties from M2020 reconstruction data

Parameter	Mean	Standard deviation (1σ)
X-J2000	2625260.7681 (m)	1.2677 (m)
Y-J2000	1864901.4022 (m)	1.6451 (m)
Z-J2000	-1072439.2998 (m)	1.9436 (m)
VX-J2000	80.7774 (m/sec)	0.0286 (m/sec)
VY-J2000	236.6885 (m/sec)	0.0268 (m/sec)
VZ-J2000	40.2203 (m/sec)	0.0353 (m/sec)
Q_I2B_0	0.54313	0.00037
Q_I2B_1	-0.22003	0.00050
Q_I2B_2	0.37693	0.00042
Q_I2B_3	-0.71729	0.00031
Roll Rate	1.6748 (deg/sec)	0.0576 (deg/sec)
Pitch Rate	3.4322 (deg/sec)	0.0574 (deg/sec)
Yaw Rate	-5.7897 (deg/sec)	0.0575 (deg/sec)
Density	0.01411 (kg/m^3)	2.1924e-5 (kg/m^3)

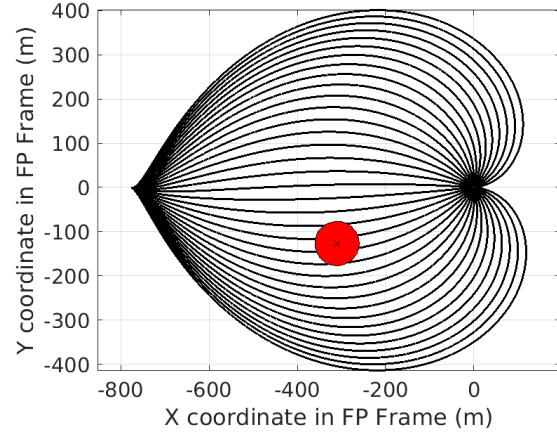
Table 2 shows the nominal states and the corresponding uncertainty considered from the M2020 reconstruction data in this work to initialize the POST2 simulation and the SMART guidance. As this work only simulates the Mars-powered divert phase, one can use the back shell separation time from the M2020 reconstruction data as the initial epoch for the simulation. 2021-02-18 20:43:56.8 TDB is considered as the simulation epoch. The POST2 is initialized using the inertial position and velocity states in J2000 coordinates shown in Table 2. Also, the POST2 is initialized using the quaternion information in Table 2 that provides the attitude of the body with respect to the inertial frame. The attitude rates are initialized using the body rates provided in Table 2. All these states are also used to initialize the SMART guidance. In addition, the density mean and uncertainty are also used to initialize the SMART guidance. This work considers the aerodynamic forces negligible for the powered divert phase. Table 1 shows the final target landing site, which is also obtained from the M2020 mission.

The vehicle is modeled similar to the M2020 for the simulation but with different specifications. The vehicle is considered to have four tanks and twelve main lander engines. The SMART guidance is only called once for these simulations to generate the reference profile. Once the guidance reference profiles are generated, SMART guidance issues commands at a frequency of 8 Hz using the reference profiles. The outer loop simulation in POST2 is run at 512 Hz. The translational controller and the quaternion controller run at 8 Hz. The POST2 uses MarsGRAM [29] to model the atmosphere in the outer loop. The POST2 considers the J2 and J3 geopotential perturbations to model the gravity. The SMART guidance only computes guidance for powered divert that ends at the beginning of the vertical descent stage. To this end, the SMART guidance requires the target terminal states for the powered divert and the final target states on the ground. The desired end state at the end of the powered divert is 250 m above the target landing site with a vertical velocity of 25 m/sec and zero horizontal velocity. In addition, the SMART guidance also has a no-go zone with the center on the ground at 18.6535 deg latitude and 77.4478 deg longitude with a radius of 50 m.

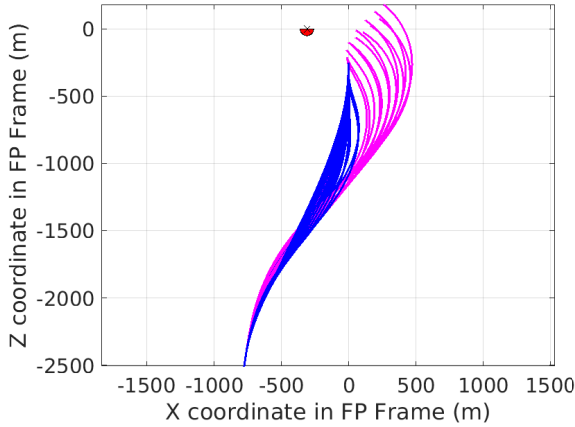
Figure 7 and Figure 8 show the positions and velocities of the vehicle along the flown trajectory along with the reference trajectories in the X-Y plane and X-Z plane within the SMART guidance. All the position and velocity



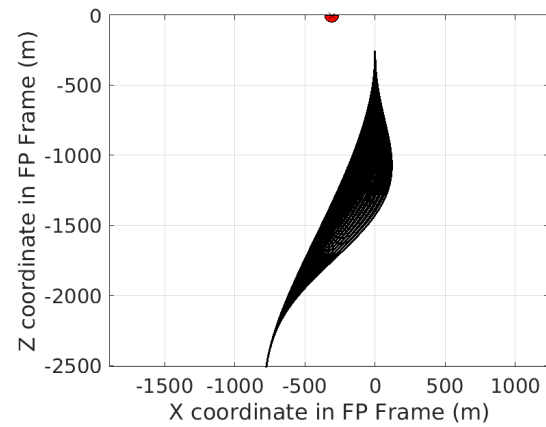
(a) Vehicle X-Y position coordinates in flat planet frame



(b) Reference X-Y position coordinates in flat planet frame



(c) Vehicle X-Z position coordinates in flat planet frame



(d) Reference X-Z position coordinates in flat planet frame

Fig. 7 Position in flat planet frame of trajectories flown by vehicle and reference trajectories within the SMART guidance

coordinates are in the flat planet coordinate system and frame. The reference trajectories in *black* are generated within the SMART guidance using the polynomials. The *blue* and *magenta* lines are the trajectories simulated within SMART guidance using the controllers and thrusters along with other models such as atmosphere and gravity. The trajectories shown in *magenta* are eliminated by the SMART guidance as they do not meet one or more of the criteria. The trajectories that require extreme maneuvers to reach the target lose performance and are therefore pruned from consideration. Among the feasible trajectories in *blue*, the SMART guidance chooses three nominal trajectories based on a scoring function to run the Monte Carlo analysis. The scoring function chooses the trajectories that require minimal fuel to accurately target the final desired states. The simulated trajectories for Monte Carlo analysis are scored using similar criteria, and the nominal trajectory corresponding to the best score Monte Carlo run is chosen as the SMART guidance's reference trajectory.

Figure 9 shows the position and velocity coordinates in the flat planet coordinates in X, Y, and Z directions from POST2 simulation. The positions and velocities in different directions as a function of time are compared between the reference trajectories and the trajectories that were flown by the vehicle using controllers and actuators. The reference trajectories are commands issued by the SMART guidance. The vehicle tracks the SMART guidance commands accurately using the translational PID controller. At the time when the guidance is initiated, the vehicle has some significant errors, most notably when analyzing the velocity components. However, these errors eventually dampen to zero. Even though the positions and velocities of the reference trajectories coincide with the vehicle's current position at

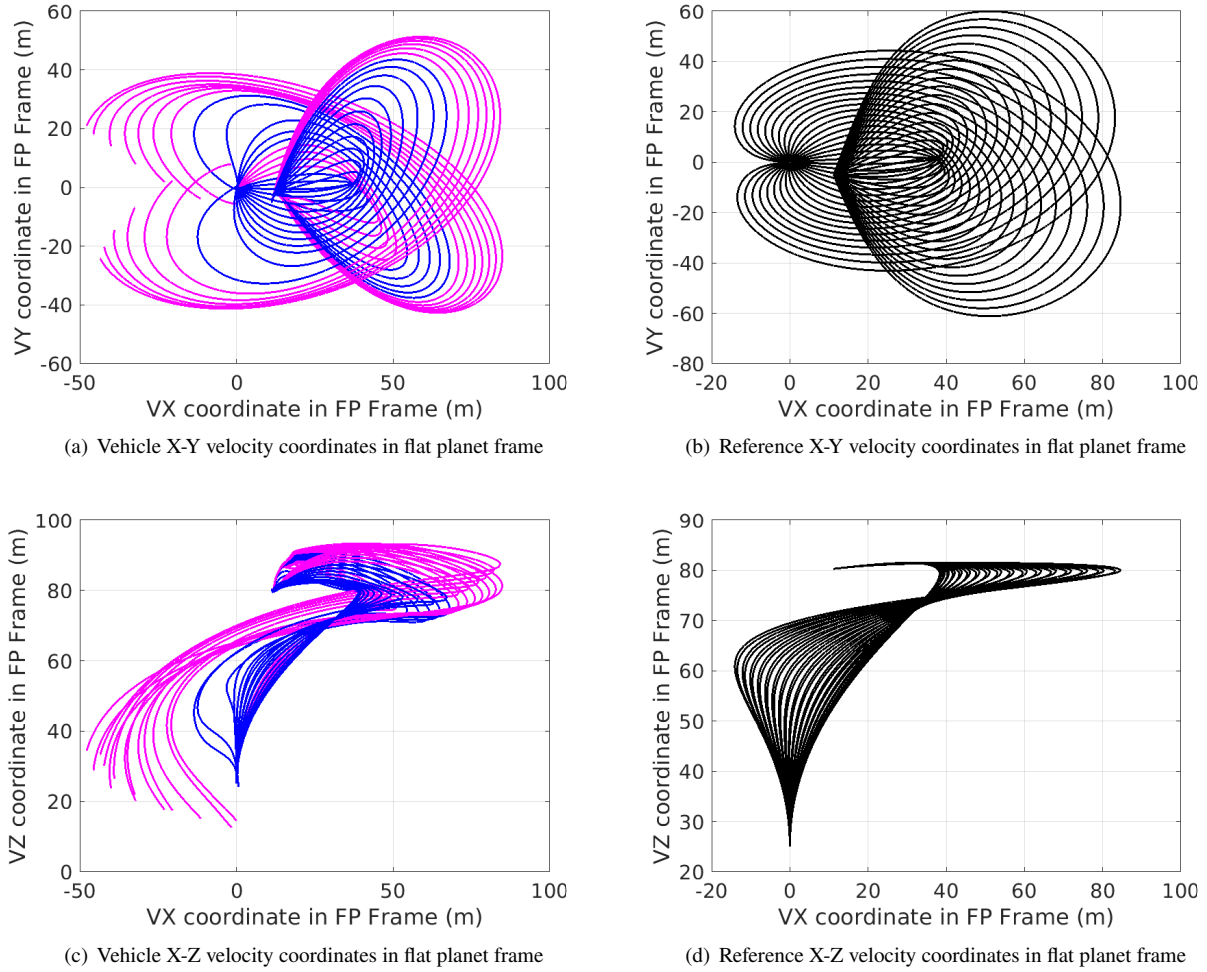
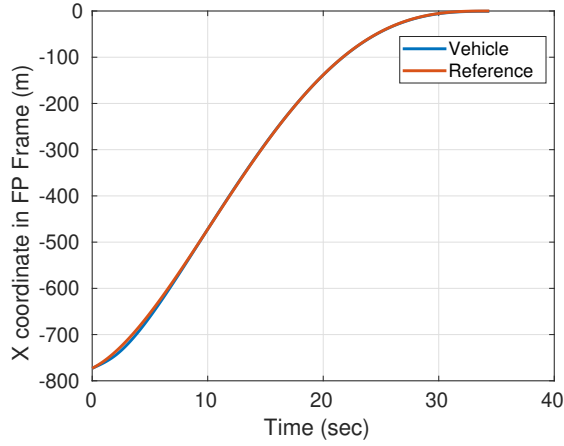


Fig. 8 Velocity in flat planet frame of trajectories flown by vehicle and reference trajectories within the SMART guidance

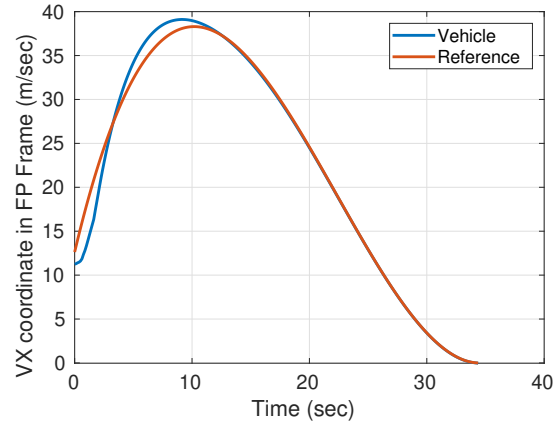
the initial time, these errors arise as the vehicle also tries to track the attitude and attitude rates along with the positions and velocities. The position in the Y-direction has about a 0.5 m error at the end. Further tuning of the PID controllers can be done to resolve these errors; but, this work assumes the 1 m accuracy to be sufficient.

Figure 10 shows the attitude and attitude rates of the vehicle simulated in the POST2 using the commands from SMART guidance. The SMART guidance provides the desired pitch and yaw commands. The roll commands are assumed to be the same as the current roll angle of the vehicle. In addition, it is desirable to have the vehicle's attitude rates be zero at the end of the power divert maneuver. The zero attitude rates for all three channels are commanded. Unlike the position and velocity, the initial attitude of the vehicle is not the same as the initial pitch and yaw commands from SMART guidance. Also, the vehicle has non-zero body rates at the initialization of the powered divert phase. As a result, the initial errors in attitude and attitude rates are much larger than in position and velocity. However, these errors settle down eventually and the vehicle sufficiently tracks the attitude and attitude rates. Tracking attitude errors is important as the thruster is considered to have a fixed pointing vector. The axial thrust command provided by the SMART guidance allows the tracking of the position and velocity only if the vehicle tracks the SMART guidance's pitch and yaw commands.

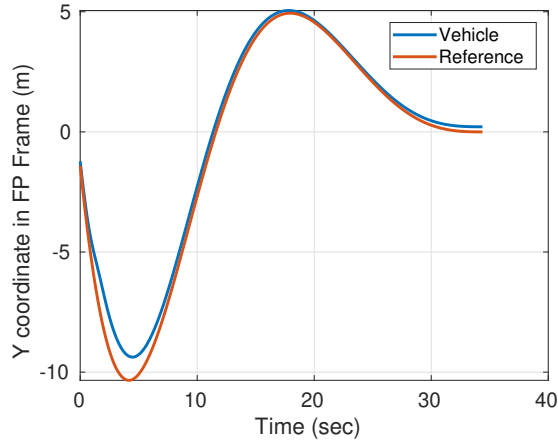
Figure 11 shows the total fuel used by the vehicle during the powered divert phase. The vehicle uses less than 350 kg of fuel during the powered divert. The rate of fuel change is not uniform, as the vehicle throttles differently to track the guidance commands. Each tank modeled in POST2 has at least 40 kg of fuel left at the end of the powered divert maneuver using the SMART guidance commands. This fuel is needed for the vertical descent of the vehicle as the



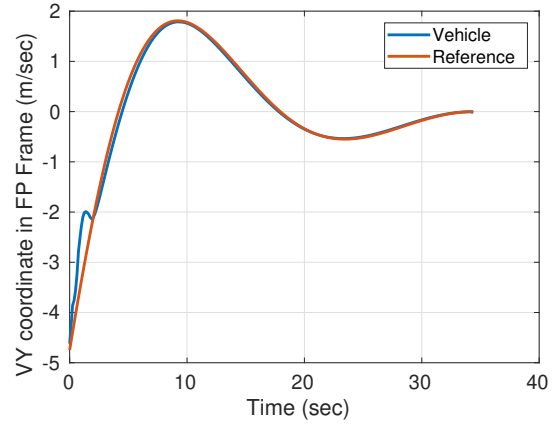
(a) X position coordinates in flat planet frame



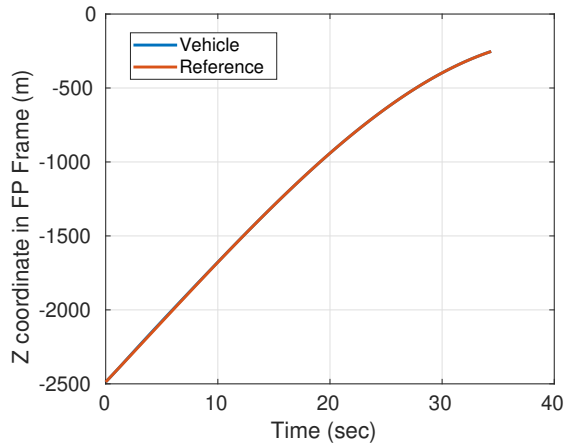
(b) X velocity coordinates in flat planet frame



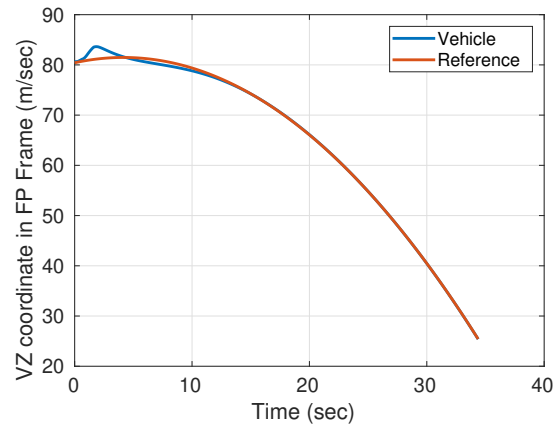
(c) Y position coordinates in flat planet frame



(d) Y velocity coordinates in flat planet frame



(e) Z position coordinates in flat planet frame



(f) Z velocity coordinates in flat planet frame

Fig. 9 Flat planet frame position and velocity coordinates of the nominal trajectory flown by vehicle and reference trajectory from SMART guidance in the outer loop simulation of POST2

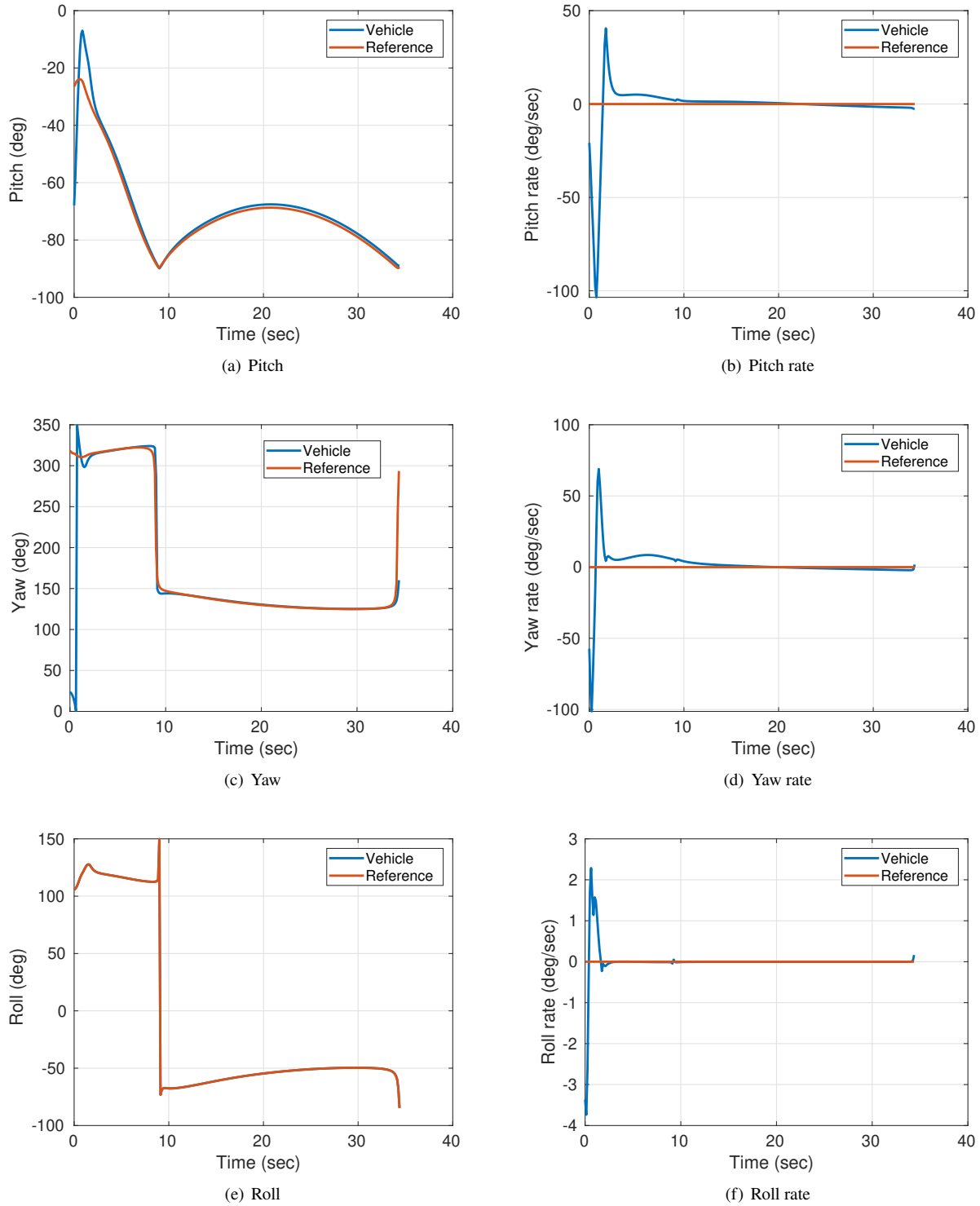


Fig. 10 Attitude and attitude rates of the nominal trajectory flown by vehicle and reference trajectory from SMART guidance in the outer loop simulation of POST2

powered divert phase only brings the vehicle 250 m above the landing target with 25 m/sec vertical velocity and zero horizontal velocity. Fuel left for vertical descent is one of the metrics that the SMART guidance checks to decide if a

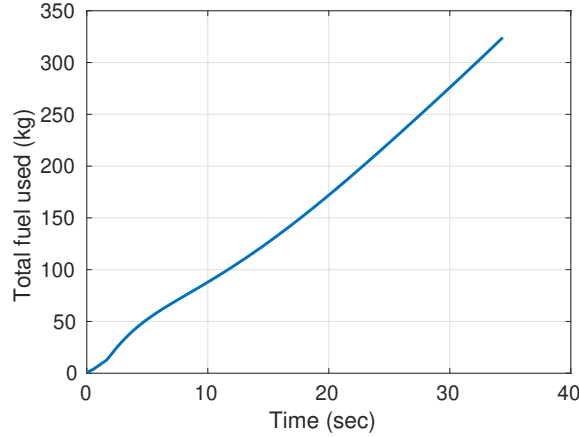


Fig. 11 Total fuel used at the end of the nominal trajectory flown by a vehicle in the outer loop simulation of POST2

candidate trajectory must be eliminated. Therefore, all the feasible trajectories within the SMART guidance analysis will have enough fuel to land the vehicle after the power divert maneuver.

V. Conclusions

This work successfully implements the SMART guidance in POST2 to simulate the powered divert at Mars. The simulation is initialized using the states and uncertainties at the back shell separation from the M2020 trajectory reconstruction. Initializing the SMART guidance using the M2020 reconstruction data is synergistic with initializing the SMART guidance using the onboard navigation filter that ingests data from several sensors such as MEDLI2. To choose the most robust and efficient guidance profile, SMART guidance simulates several trajectories within the trajectory design map, and three Monte Carlo analyses are run on the top three candidate trajectories. This work uses traditional Monte Carlo analysis instead of Multi-Fidelity Monte Carlo (MFMC) analysis, as its primary focus is to integrate SMART guidance with other simulation frameworks such as POST2. In this work, POST2 simulates the powered divert using the commands from the SMART guidance that are issued using the reference trajectory obtained from the analysis conducted within the SMART guidance. The POST2 simulation tracks these guidance commands effectively using PID controllers and the thrust allocator. This work uses the POST2 simulation to show that SMART guidance can autonomously plan safe, robust, and precise trajectories.

References

- [1] kat Troche, "Landing On Mars: A Tricky Feat!" , 2024. URL <https://science.nasa.gov/solar-system/skywatching/night-sky-network/landing-on-mars-a-tricky-feat/>.
- [2] Farley, K. A., Williford, K. H., Stack, K. M., Bhartia, R., Chen, A., de la Torre, M., Hand, K., Goreva, Y., Herd, C. D., Hueso, R., et al., "Mars 2020 mission overview," *Space Science Reviews*, Vol. 216, 2020, pp. 1–41.
- [3] Prakash, R., Burkhart, P. D., Chen, A., Comeaux, K. A., Guernsey, C. S., Kipp, D. M., Lorenzoni, L. V., Mendeck, G. F., Powell, R. W., Rivellini, T. P., et al., "Mars Science Laboratory entry, descent, and landing system overview," *2008 IEEE Aerospace Conference*, IEEE, 2008, pp. 1–18.
- [4] Vandermeij, N., and Paczkowski, B., "The Cassini-Huygens Mission Overview," *SpaceOps 2006 Conference*, 2006, p. 5502.
- [5] Muirhead, B. K., Nicholas, A., and Umland, J., "Mars sample return mission concept status," *2020 IEEE Aerospace Conference*, IEEE, 2020, pp. 1–8.
- [6] Lorenz, R. D., Turtle, E. P., Barnes, J. W., Trainer, M. G., Adams, D. S., Hibbard, K. E., Sheldon, C. Z., Zacny, K., Peplowski, P. N., Lawrence, D. J., et al., "Dragonfly: A rotorcraft lander concept for scientific exploration at Titan," *Johns Hopkins APL Technical Digest*, Vol. 34, No. 3, 2018, p. 14.

- [7] Linck, E., Crane, K. W., Zuckerman, B. L., Corbin, B. A., Myers, R. M., Williams, S. R., Carioscia, S. A., Garcia, R., and Lal, B., Evaluation of a Human Mission to Mars by 2033, IDA Science and Technology Policy Institute Washington, DC, 2019.
- [8] Singh, G., SanMartin, A. M., and Wong, E. C., "Guidance and control design for powered descent and landing on Mars," 2007 IEEE Aerospace Conference, IEEE, 2007, pp. 1–8.
- [9] Lu, P., Cerimele, C. J., Tigges, M. A., and Matz, D. A., "Optimal aerocapture guidance," Journal of Guidance, Control, and Dynamics, Vol. 38, No. 4, 2015, pp. 553–565.
- [10] Scharf, D. P., Açıkmeşe, B., Dueri, D., Benito, J., and Casoliva, J., "Implementation and experimental demonstration of onboard powered-descent guidance," Journal of Guidance, Control, and Dynamics, Vol. 40, No. 2, 2017, pp. 213–229.
- [11] Nelessen, A., Sackier, C., Clark, I., Brugarolas, P., Villar, G., Chen, A., Stehura, A., Otero, R., Stilley, E., Way, D., et al., "Mars 2020 entry, descent, and landing system overview," 2019 IEEE aerospace conference, IEEE, 2019, pp. 1–20.
- [12] Little, A., Bose, D., Karlgaard, C., Munk, M., Kuhl, C., Schoenenberger, M., Antill, C., Verhappen, R., Kutty, P., and White, T., "The Mars Science Laboratory (MSL) entry, descent and landing instrumentation (MEDLI): hardware performance and data reconstruction," 36th AAS Guidance and Control Conference, 2013.
- [13] Hwang, H., Bose, D., Wright, H., White, T. R., Schoenenberger, M., Santos, J., Karlgaard, C. D., Kuhl, C., Oishi, T., and Trombetta, D., "Mars 2020 entry, descent, and landing instrumentation (MEDLI2)," 46th AIAA Thermophysics Conference, 2016, p. 3536.
- [14] Powell, W. A., "High-performance spaceflight computing (hpsc) project overview," Radiation Hardened Electronics Technology Conference (RHET) 2018, 2018.
- [15] Rutishauser, D., Moore, R., Prothro, J., and Yim, H., "High performance computing for precision landing and hazard avoidance and co-design approach," 2019 IEEE Aerospace Conference, IEEE, 2019, pp. 1–10.
- [16] Swope, J., Mirza, F., Dunkel, E., Candela, A., Chien, S., Holloway, A., Russell, D., Sauvageau, J., Sheldon, D., and Fernandez, M., "Benchmarking space mission applications on the snapdragon processor onboard the iss," Journal of Aerospace Information Systems, Vol. 20, No. 12, 2023, pp. 807–816.
- [17] Williams, R. A., Green, J., and Striepe, S., "Entry, Descent, and Landing: Current State of HPC for EDL," High Performance Computing Incubator Technical Interchange Meeting, 2020.
- [18] Lugo, R. A., Shidner, J. D., Powell, R. W., Marsh, S. M., Hoffman, J. A., Litton, D. K., and Schmitt, T. L., "Launch vehicle ascent trajectory simulation using the Program to Optimize Simulated Trajectories II (POST2)," AAS/AIAA Space Flight Mechanics Meeting, 2017.
- [19] Green, J. S., "Onboard Autonomous Trajectory Planner," Ph.D. thesis, University of Virginia, Charlottesville, April 2019.
- [20] Thompson, M., Geraci, G., Bomarito, G., Warner, J., Leser, P., Leser, W. P., Eldred, M. S., Jakeman, J., and Gorodetsky, A., "Strategies for automation of model tuning in multi-fidelity trajectory uncertainty propagation," AIAA SCITECH 2023 Forum, 2023, p. 1481.
- [21] Braun, R. D., Powell, R. W., Engelund, W. C., Gnoffo, P. A., Weilmuenster, K. J., and Mitcheltree, R. A., "Mars Pathfinder Six-Degree-of-Freedom Entry Analysis," Journal of Spacecraft and Rockets, Vol. 32, No. 6, 1995, pp. 993–1000. <https://doi.org/10.2514/3.26720>.
- [22] Desai, P. N., Schoenenberger, M., and Cheatwood, F. M., "Mars Exploration Rover Six-Degree-of-Freedom Entry Trajectory Analysis," Journal of Spacecraft and Rockets, Vol. 43, No. 5, 2006, pp. 1019–1025. <https://doi.org/10.2514/1.6008>.
- [23] Desai, P. N., Prince, J. L., Queen, E. M., Schoenenberger, M., Cruz, J. R., and Grover, M. R., "Entry, Descent, and Landing Performance of the Mars Phoenix Lander," Journal of Spacecraft and Rockets, Vol. 48, No. 5, 2011, pp. 798–808. <https://doi.org/10.2514/1.48239>.
- [24] Way, D., Davis, J., and Shidner, J., "Assessment of the Mars Science Laboratory Entry, Descent, and Landing Simulation," AAS 13-420, AAS/AIAA Space Flight Mechanics Conference, Kauai, HI, 2013.
- [25] Maddock, R., Cianciolo, A., Korzun, A., Litton, D., Zumwalt, C., and Karlgaard, C., "InSight Entry, Descent, and Landing Postflight Performance Assessment," Journal of Spacecraft and Rockets, Vol. 58, No. 5, 2021, pp. 1530–1537. <https://doi.org/10.2514/1.A35023>.

- [26] Way, D., Dutta, S., Zumwalt, C., and Blette, D., “Assessment of the Mars 2020 Entry, Descent, and Landing Simulation,” AIAA 2022-0421, AIAA SciTech 2022, AIAA Atmospheric Flight Mechanics Conference, San Diego, CA, 2022.
- [27] Smith, H., “Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2),” , 2020. URL <https://www.nasa.gov/directorates/stmd/mars-entry-descent-and-landing-instrumentation-2-medli2/>.
- [28] Karlgaard, C. D., Schoenenberger, M., Dutta, S., and Way, D. W., “Mars entry, descent, and landing instrumentation 2 trajectory, aerodynamics, and atmosphere reconstruction,” Journal of Spacecraft and Rockets, Vol. 60, No. 1, 2023, pp. 199–214.
- [29] Justh, H., Justus, C., and Ramey, H., “Mars-GRAM 2010: Improving the precision of Mars-GRAM,” fourth international workshop on the Mars atmosphere: Modelling and observations, 2011.