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GUIDANCE, NAVIGATION AND CONTROL FOR THE ENTRY, DESCENT, AND LANDING OF THE MARS 2020 MISSION

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This paper presents an overview of the Guidance, Navigation and Control (GNC) system for the Entry, Descent, and Landing (EDL) phases of the Mars 2020 Mission. The EDL GNC system adds Terrain Relative Navigation to the MSL EDL GNC system[1] to enable landing on landing sites with landing hazards within the landing ellipse. This paper describes the GNC architecture, including sensors, actuators and algorithms, for the entry, parachute descent, and powered flight phases of the mission.

INTRODUCTION

The Mars 2020 project is a rover mission in development with a projected launch date in the summer of 2020 and landing on Mars in February of 2021. The main objectives of this rover mission are to seek past life in Mars, collect rock samples for potential future return to Earth, and prepare for humans.

This mission extensively leverages the Cruise, EDL and Rover designs from Curiosity (2012). The Rover (15% heavier than Curiosity) includes a new suite of science instruments tailored to the Mars 2020 science objectives.

The EDL GNC system is mostly built-to-print from MSL, but with some minor fixes and enhancements. This paper is organized as follows, section 2 describes the hardware used by the GNC system, section 3 describes the phases of EDL and subsequent sections will then describe the GNC system for each phase of the mission focusing on changes from the MSL design[1]. The paper concludes with a discussion on EDL impacts and a conclusion section.

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EDL GNC-RELEVANT HARDWARE

On the Entry Capsule, shown on Figure 1, there can be seen two set of ejectable balance masses: the cruise balance masses (two ~70 kg masses) and the entry balance masses (six ~23kg masses). There are also, 4 pods of RCS thrusters with 2 thrusters each. These thrusters operate in blowdown and regulated modes providing 170N and 250N per thruster respectively. The thrusters operate at 8 Hz in pulse width modulation mode with a commendable minimum on-time of 30 ms.

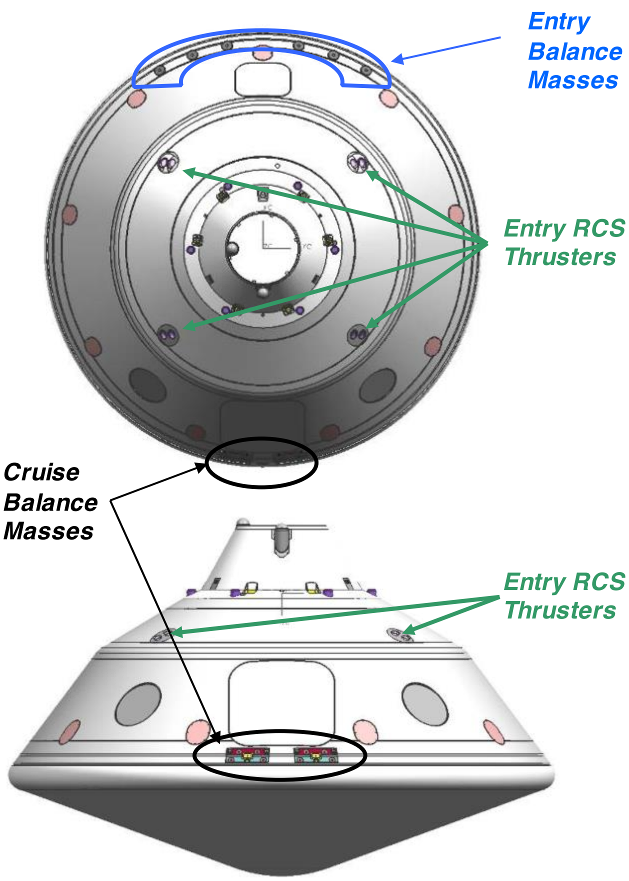

Figure 1. Entry Capsule.

Figure 2 shows the descent vehicle, which includes the GNC sensors. Two descent IMUs (each has 3 DOF gyros and 3 DOF accels) and a landing radar also called Terminal Descent Sensor (TDS). The TDS is a ka-band (35 GHz) Doppler radar with 6 narrow beam antennas (~ 3 deg beamwidth). The TDS generates a single slant-range and ground relative velocity at 20 Hz. During the different phases of flight, the TDS is re-configurable to enable selecting which antennas are used during a given phase. The Lander Vision System (LVS) is a new GNC sensor added for Mars 2020. The LVS is composed of a ~90 FOV camera and a vision compute element within the rover chassis. In addition, the descent vehicle has eight throttleable Mars Landing Engines (MLEs), which can be commanded at 64 Hz and each can produce thrust in the range 300-3200N.

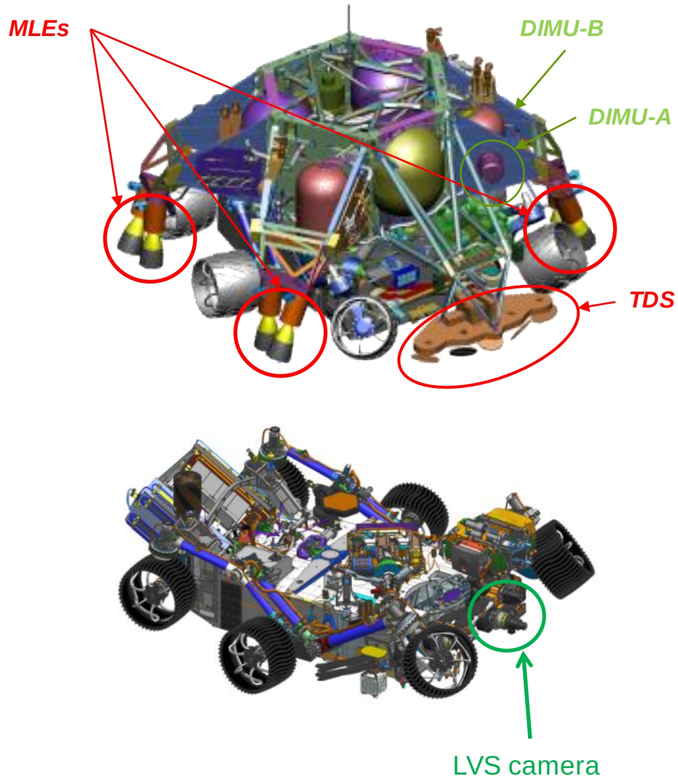

Figure 2. Descent Vehicle and Stowed Rover

EDL PHASES

Figure 3 shows the main phases of EDL. exo-atmospheric, entry, parachute descent and powered descent phases.

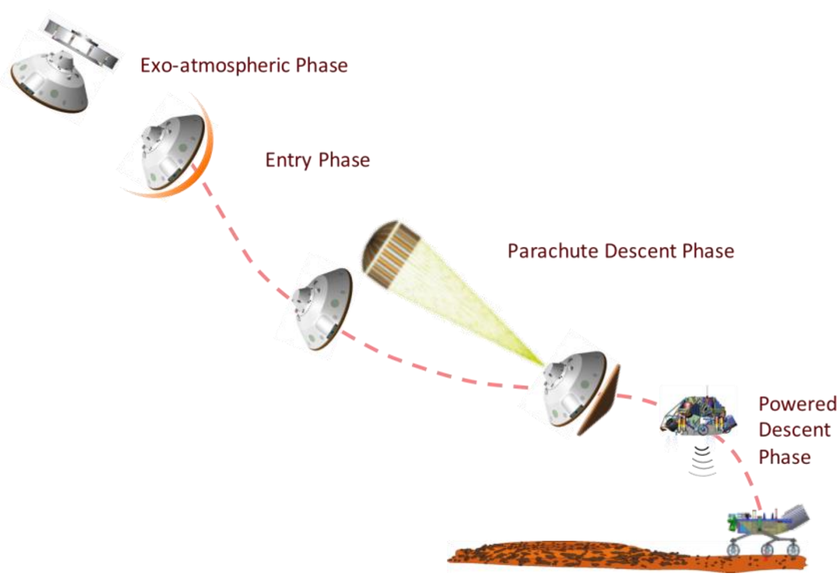

Figure 3. EDL phases

The Mars 2020 EDL GNC design is built-to-print from the MSL EDL GNC design except for:

- Fixing the touchdown velocity anomaly
- Changing the parachute deploy trigger to reduce the landing ellipse
- Adding Terrain Relative Navigation (TRN) to enable hazards within the landing ellipse

We will discuss these changes during the phase that they occur.

Each EDL phase has a different GNC system. The EDL GNC mode commander is a state machine that precisely defines the behavior of the EDL GNC system over the entire EDL. It specifies which GNC functions are performed at each mode and the conditions to transition between modes, called mode triggers.

EXO-ATMOSPHERIC PHASE GNC

During the exo-atmopheric phase of the mission, the vehicle will spindown (from the 12 RPM of the cruise configuration) and turn to a predicted entry attitude to be ready for guidance start. In addition, it will eject the cruise balance masses to create a CG offset that will generate a lift vector during the entry phase. Figure 4 illustrates the block diagram of the GNC system during the atmospheric phase.

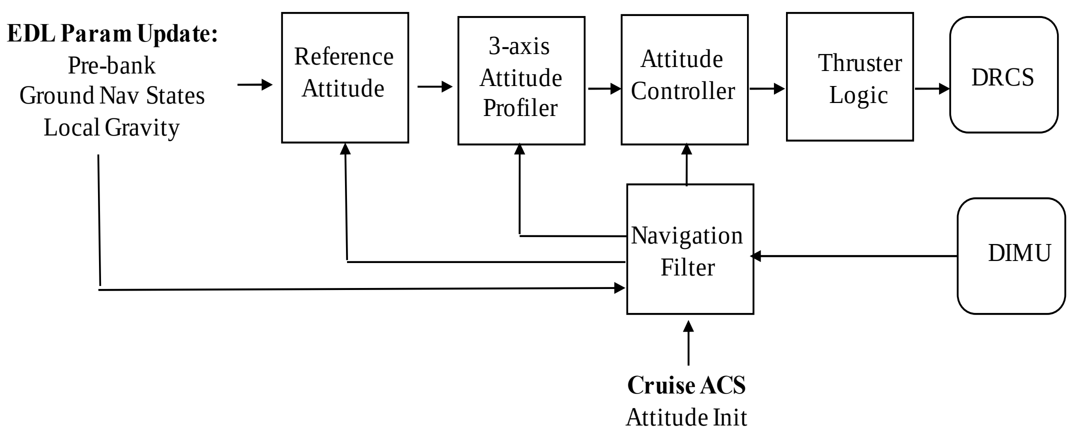

Figure 4. Exo-atmospheric GNC

The EDL parameter update ground command provides a predicted bank command (pre-bank), ground derived navigation states to seed the navigation filter and a local gravity correction to the to the onboard J2 gravity model. The local gravity correction is new for Mars 2020. This parameter was added to mitigate the MSL touchdown velocity anomaly.

During this phase of the mission, the GNC system is three-axis attitude control system. The reference attitude block is a 3-axis attitude commander, which creates the reference attitude from the pre-bank and the predicted trim angle of attack at the beginning of entry guidance. The trim angle of attack varies as a function of aerodynamic moments during the entry phase. The predicted trim angle of attack is parameterized by entry speed. The entry speed provided by the navigation filter is used to select the value to be used. The three-axis attitude profiler generates the typical attitude profile (cancel rate, accelerate, coast, and decelerate phases). The entry controller feedforward control path implements the attitude profile and the feedback control path (phase plane controller) corrects for errors in tracking the profile by using attitude estimates from the navigation filter. The thruster logic generates the RCS thruster commands needed to get the torque requested by the entry controller.

At the predicted entry time, the vehicle pressurizes the RCS thrusters and then waits for the entry guidance trigger (sense 0.2 g deceleration) to transition into the entry phase.

ENTRY PHASE GNC

During the entry phase, an Apollo-derived entry guidance algorithm[1] is used and has two main phases: (i) range control and (ii) and heading alignment. The entry guidance algorithm generates bank angle commands. These bank angle commands are of two classes: large bank angle command changes when algorithms are first called or for bank reversals; and small bank angle corrections during the range control and heading alignment tracking phases.

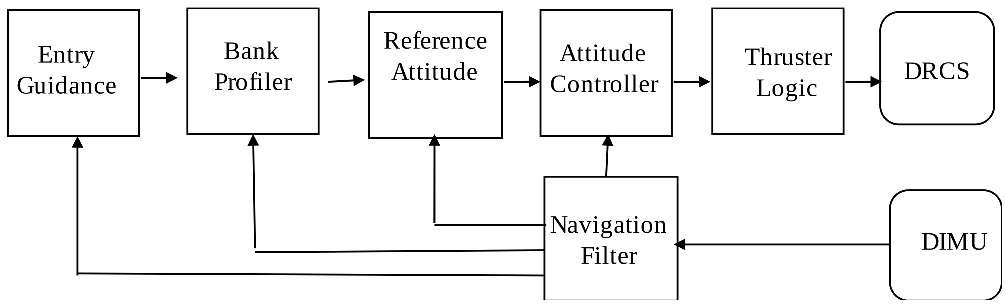

Figure 5. Entry GNC

The entry GNC block diagram is shown in Figure 5. The guidance bank commands go to the bank profiler, a single-axis attitude profiler, which will generate a slew profile for the large bank commands. Then, the attitude commander will generate a reference 3-axis attitude by combining the bank command with the predicted trim angle of attack. The predicted trim angle of attack is scheduled based on entry speed. The reference attitude is then fed to the attitude controller, which creates correction torques, by comparing with the estimated attitude from the navigation filter. The desired torques are then implemented by the thruster logic.

The entry phase concludes with the Straighten Up and Flight Right (SUFR) maneuver that removes the angle of attack by ejecting the entry balance masses and rolls the vehicle to point the TDS antennas towards the ground. For Mars 2020, we have changed the SUFR trigger and parachute deploy triggers. We have changed the SUFR trigger from a velocity trigger to a velocity-constraint downrange trigger.

- Trigger IF ([Vel < Vel_max AND Downrange < Downrange_threshold] OR [Vel <= Vel_min])

The velocity constraints are to protect against unknown/unknowns. Triggering at too high a velocity could lead to higher parachute loads or large attitude rates from aero-oscillations. Triggering at a too low velocity could lead to altitude losses, which reduce the EDL timeline margin.

The parachute deployment trigger has also been changed from a velocity trigger to be a fix time offset (14 s) from the SUFR trigger, to enable completing the maximum possible slew of 180 deg.

The change to a downrange trigger reduces the landing ellipse from 19x7 km (Semimajor x Semiminor axis) to 8x7 km. Figure 6 shows a comparison of the Mars 2020 landing ellipse to previous mars missions.

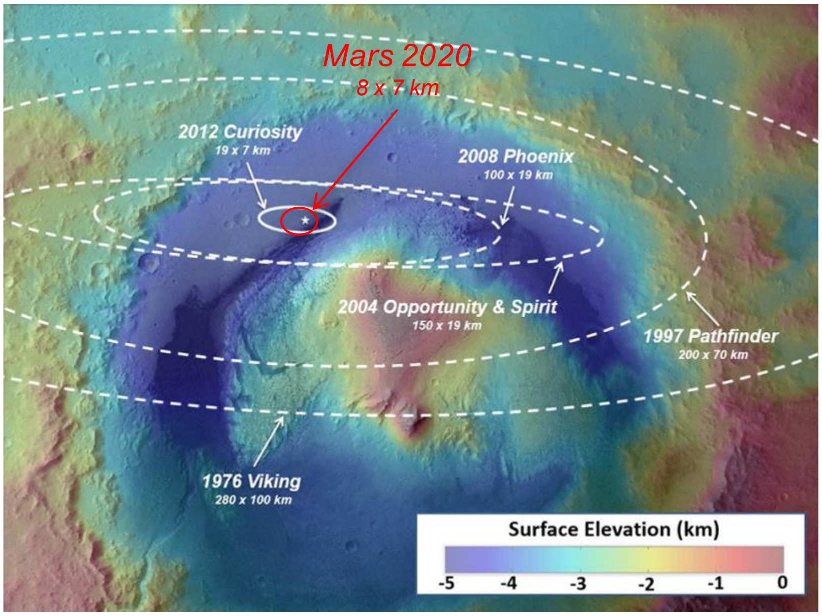

Figure 6. Mars 2020 landing ellipse compared to previous missions (superimposed on the Gale crater elevation map)

PARACHUTE DESCENT PHASE GNC

In this phase, the GNC goes back to RCS control to damp parachute induced attitude dynamics, which are dominated by capsule swinging and coning under the parachute often denominated parachute wrist mode. The block diagram in Figure 7 shows the reuse of the same navigation filter, reference attitude commander, attitude controller, thruster logic as during entry but tuned for this phase. However, because of concerns about RCS firings damaging the parachute, the attitude controller is tuned to have very large deadbands. In this phase, after the vehicle reaches conditions suitable for the heatshield ejection, it ejects the heatshield and then turns on the landing radar. The main objective of the navigation filter in this phase is to continue propagating position and attitude and also estimate ground relative position by using measurements from the landing radar.

In this phase, Mars 2020 has added a new capability: Terrain Relative Navigation (TRN). This capability allows to have hazards of about 100 m in size within the landing ellipse as long as hazards are surrounded by hazard safe buffer zone of 120 m (60 m is the 99%-tile error in performing TRN).

TRN is composed of two main parts: (i) a new sensor, the Lander Vision System[2] (LVS) composed of a camera and a vision compute element to provide map relative localization and (ii) a Safe Target Selection (STS) to select a landing target from an on-board Safe Targets Map within a reachable region.

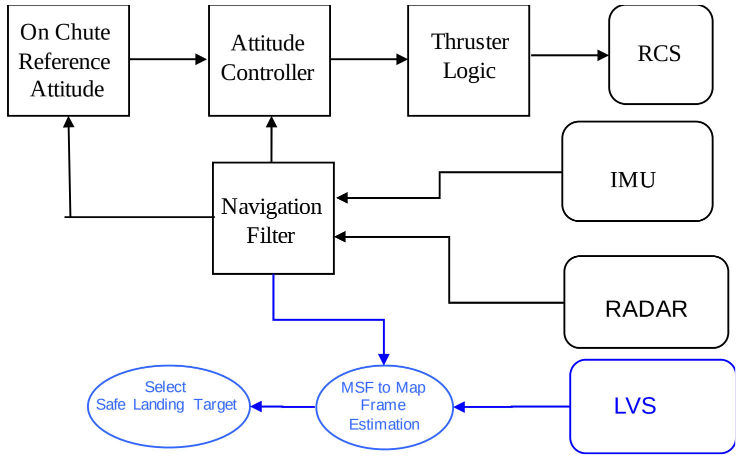

Figure 7. On-chute GNC (blue indicates the new elements added for TRN)

After been initialized with a surface relative state, the LVS starts to perform map relative localization at 4200 m above the ground and within 6 seconds produces a reduced performance localization solution, which is accurate to 54 meters, and within 10 seconds produces a nominal performance localization solution, which is accurate to 40 meters. When valid solutions are created every 1 to 2 seconds, the GNC mode commander will update the Mars Surface Frame (MSF) to Map Frame coordinate transformation.

Safe Targets Map

The Safe Targets Map (STM) is an onboard map. It covers an area of 20x20 km over the landing ellipse with a 10x10 m pixel resolution. Each pixel has a safe target level (0-255). The map size, resolution and number of levels were selected to minimize memory use impact on the heritage MSL design. The safe targets levels are assigned to indicate a landing risk (% landing failure risk) and if the pixel has benign slopes (slope <10 deg). The benign slope feature allows to favoring landing on smaller slopes for landing targets that have the same landing hazard risk. The levels are then discretized to have a resolution of 5% in risk from 100% to 10%, and 0.1% in risk from 10% to 0.1% risk. Figure 8 depicts this discretization.

```
0: No data
1:   100% risk and non benign slope
2:   100% risk and benign slope
3:    95% risk and non benign slope
4:    95% risk and benign slope
       ...
35:   15% risk and non benign slope
36:   15% risk and benign slope
37:   10% risk and non benign slope
38:   10% risk and benign slope
39:  9.9% risk and non benign slope
40:  9.9% risk and benign slope
       ...
235: 0.1% risk and non benign slope
236: 0.1% risk and benign slope
```

Figure 8. Safe Target Maps levels

The Safe Targets Map is generated from the Mars 2020 Council of Terrain's landing hazard and slope maps. These two maps cover an area of roughly ~25x25 km, and have a resolution of 1x1 m/pixel. These maps are first transformed from a Lat/Lon grid to a Cartesian grid in the STM frame. Then, the hazards and slopes are buffered by applying a padding kernel to account for TRN knowledge and control errors. The padded hazard and slope maps are then coarsened to 10x10 m pixels and used to assign the safe target levels for each pixel of the safe targets map.

Safe Target Selection

The Safe Target Selection (STS) starts at the backshell separation trigger by computing the zero-divert point. This point is then used to place the reachable regions (called wedges because of their shape) on the STM. Figure 9 illustrates the shape of a wedge. The reachable wedge are parameterized by a divert radius and azimuth from the zero-divert point and divert direction (e.g. 300 < radius < 635 meters and -25 < azimuth < 25 degrees). There are two wedges, that correspond to divert directions associated with the MSL heritage backshell avoidance algorithm out-of-plane vectors. Then, the algorithm searches each of the two wedges for the safest landing target pixel on each one. If there are more than one pixel with the safest level it uses the following cost function

$$J(r, az) = \frac{|r - r_{center}|}{d_r} + f_p \frac{|az - az_{center}|}{d_{az}}$$

where, r_{center} and az_{center} define the center of the wedge with respect to the zero-divert point, and the d_r = 167.5 m and d_{az} = 25 deg. define the size of wedge. The cost allows to aim for the center of the wedge. The cost function has a penalty factor, f_p, to penalize the weight of the azimuth term on the cost. This cost allows to balance fuel use with backshell recontact risk. Note that fuel use is proportional to divert distance, and backshell recontact risk increases with azimuth angle.

To limit the computational loading of the flight computer the search is spread over 2.6 sec, while the vehicle performs the activities to separate from the backshell. At the time to plan the backshell avoidance divert, the prime wedge is defined by the out-of-plane-sign per the MSL heritage Backshell avoidance algorithm. If the prime wedge best safe target is better than the one from the reverse wedge, it selects it. If the reverse wedge best safe target is better than the one from the prime wedge by more than a threshold, it will go to the reverse wedge. This allows to trade landing risk with backshell recontact risk that is slightly higher for the reverse wedge.

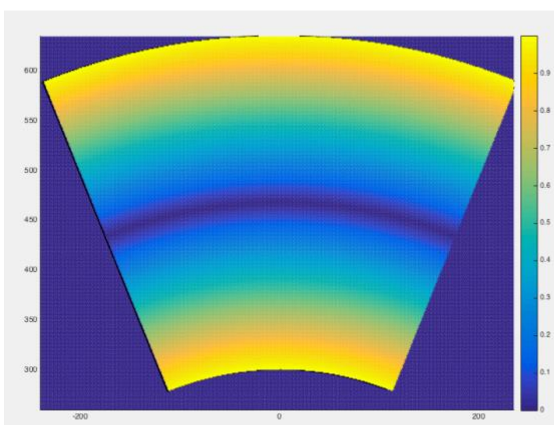

Figure 9. Reachable wedge and wedge cost function (f_p = 0) evaluated at each location.

POWERED DESCENT PHASE GNC

The GNC block diagram for the powered descent phase is shown in Figure 10. The figure shows a 6-DOF GNC system. The navigation filter fusions the TDS and IMU data to estimate altitude and ground relative velocity. The powered descent guidance laws generate position and attitude trajectory profiles. In addition, there are three controllers, a vertical position controller, a horizontal position controller, and an attitude controller. The horizontal position control is achieved via the attitude controller since the MLE are body fixed engines, which requires turning the vehicle to achieve a horizontal motion. The engine mixing logic algorithm calculates the 8 MLE throttle levels needed to achieved the commanded vertical force requested by the vertical loop and the commanded torque requested by the attitude loop.

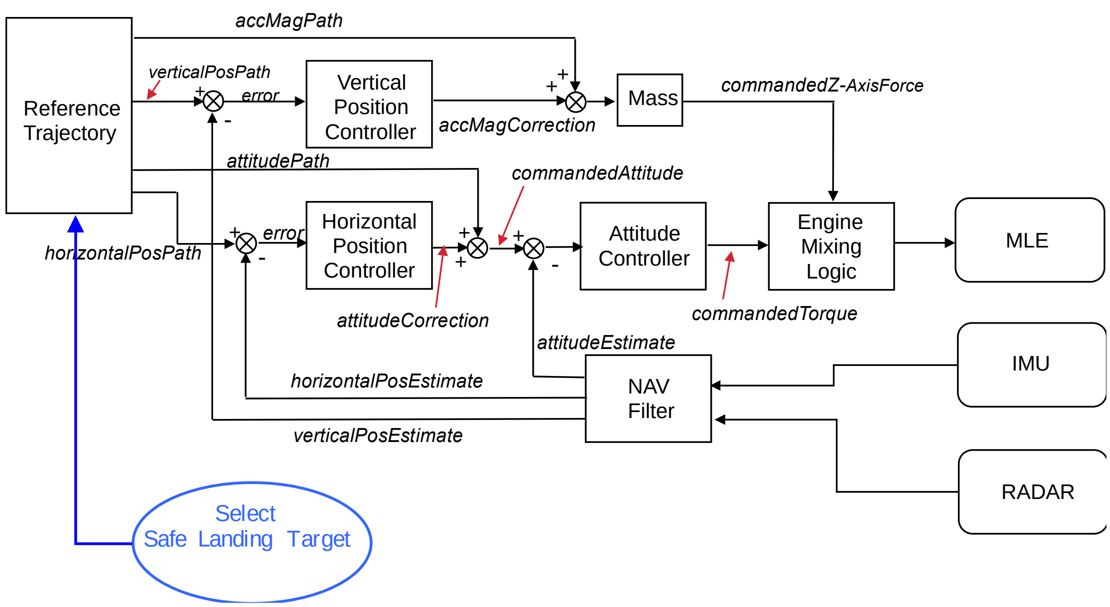

Figure 10. EDLGNC Powered Flight Control Block Diagram (blue indicates the new element added for TRN)

The main objectives of the powered descent phase are:

1. Perform the divert to the selected safe target while avoiding the backshell
2. Enable trajectory corrections that reduce altitude knowledge errors over time. Altitude errors are due to radar measurement errors and to errors from measuring the terrain in the vicinity of the landing site.
3. Perform the skycrane, detect touchdown and command the flyaway.

The first objective is achieved via the powered approach that performs a 300-635 m diverts out of plane to evade the backshell. The second objective is achieved throughout via trajectory planing capability at mode transitions (nominal) and when large errors are encounter (off-nominal). Figure 11 illustrates how the altitude errors are managed over time through the powered descent modes.

MSL had an inflight anomaly during landing. MSL touchdown velocities were outside the specified requirements. MSL vertical touchdown velocity was 0.63 m/s (Req. 0.75 ± 0.1 m/s), and horizontal touchdown velocity was 0.18 m/s (MSL Req. 0 ± 0.1 m/s). The root causes were:

- Local gravity differed from onboard gravity model by -4.4 mm/s2. Which resulted in lower than expected vertical velocity and contamination of horizontal velocity
- "Sandy radar" – MLE plumes created fast-moving dust which corrupted the radar measurements. This led to increased horizontal velocity errors.

To mitigate the vertical velocity issue, Mars 2020 is adding a local gravity correction parameter to the onboard gravity model. The NASA Mars program office has been developing a high-fidelity Mars gravity map that will be used to derive this parameter.

In addition, to further mitigate the horizontal velocity issue, Mars 2020 has tightened the attitude initialization requirement, also retuned the Navigation Filter to provide better filtering of the suspect radar measurements. In addition, the horizontal requirement has been relaxed to 0 ± 0.4 m/s, which is within the MSL capability.

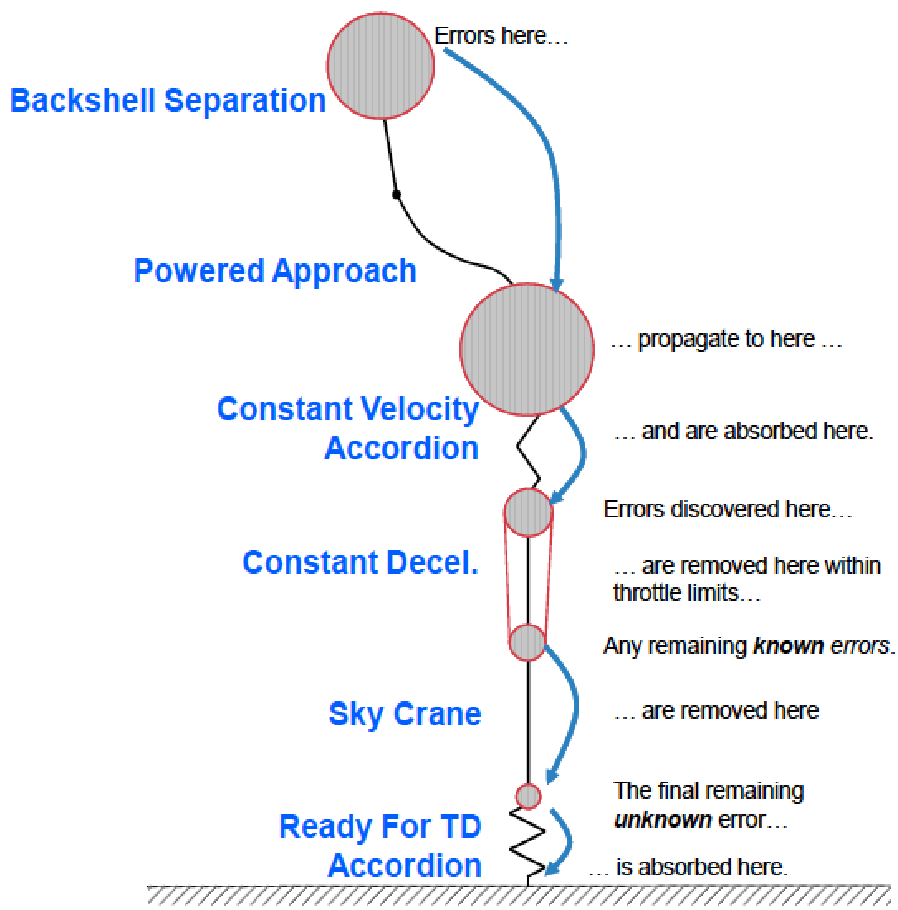

Figure 11. Altitude error management through the Powered Descent phase

SIMULATION RUN

In this section, we show results form a simulation run from the GNC Simulation Test Set (GSTS), which was upgraded from MSL to include a behavioral model of the LVS and prototype code for the Safe Target Selection algorithm. Figure 12 shows birdes eye views of vehicle trajectory over the STM and hazard maps.

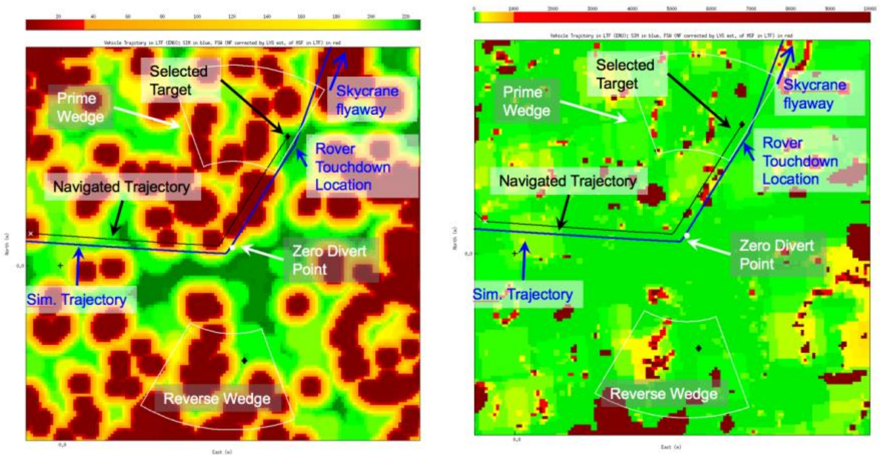

Figure 12. Trajectory over STM and Hazard Maps

The figure has been annotated to indicate the zero-divert point, the prime and reverse wedges, the navigated trajectory from FSW telemetry and the truth simulated trajectory. The errors between the navigated and the truth trajectories motivates the need to buffer the hazards with the padding kernel. By comparing the maps it can be observed the effect of the padding kernel which buffers the hazards.

IMPACTS ON THE EDL SYSTEM

The range trigger could have an impact in EDL margins (parachute loads and parachute deploy altitude loss) if the parachute deploy occurs at high or low velocities. However, velocity constraints on the trigger limit these risks.

The addition of TRN required using up some of the MSL EDL excess margins. MSL landed with 80 kg of fuel in the tank. The addition of TRN requires an additional 35 kg to be able to perform the larger diverts. In addition, it tightens up the navigation filter requirements. In MSL, the navigation filter needed to acquire the ground and converge by 3000 m altitude to trigger priming of the MLEs. In Mars 2020, we now need the navigation filter to have converged by 4200 m to initialize the Lander Vision System. In MSL the radar had an excellent performance, the navigation filter converged at 8.3 km altitude providing vast timeline margin to the 3000 m.

EDL and GNC are keeping watch on other key performance variables to guarantee that they stay within the MSL design envelope. Example metrics include radar off-nadir angles and control authority during the divert.

In addition, if TRN were to fail, there is graceful degradation. The Mars 2020 candidate landing sites are approx. 90% safe, if TRN failed, the software will revert to the MSL divert and land there. In this failed scenario, the risk of landing on a hazard will increase from approximately 0.5% to 10%.

CONCLUSIONS

In this paper, we have provided a high level overview of the GNC design for the Mars 2020 mission focusing on changes from the MSL heritage design. The fixing of the MSL touchdown velocity anomaly, and the addition of two enhancements: the range trigger to reduce the lading ellipse and Terrain Relative Navigation (TRN) to enable landing hazards within the landing ellipse.

These changes were architected in a way to minimize the impact to the MSL heritage hardware and software. The addition of TRN required using some of the excess capability from MSL. Impacts to EDL margins are small and the EDL system maintains healthy and balanced margins.

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