Attitude Controller for the Atmospheric Entry of the Mars Science Laboratory

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This paper describes the attitude controller for the atmospheric entry of the Mars Science Laboratory (MSL). The controller will command 8 RCS thrusters to control the 3-axis attitude of the entry capsule. The Entry Controller is formulated as three independent channels in the control frame, which is nominally aligned with the stability frame. Each channel has a feedfoward and a feedback path. The feedforward path enables fast response to large bank commands. The feedback path stabilizes the vehicle angle of attack and sideslip around its trim position, and tracks bank commands. The feedback path has a PD/D control structure with deadbands that minimizes fuel usage. The performance of this design is demonstrated via computer simulations.

I. Introduction

THIS paper describes the concept for the attitude controller for the exo-atmospheric and guided entry phases of the Mars Science Laboratory (MSL) Entry, Descend and Landing (EDL). MSL is the next rover mission to Mars which will be launched in 2009. This paper supersedes an earlier design which was presented in [1]. An overview of the GN&C for MSL EDL is given in [2].

The exo-atmospheric phase starts after separation from the Cruise stage until the capsule enters the Martian atmosphere. The guided entry phase takes the vehicle through the Martian atmosphere from hypersonic speeds (~ mach 30) to supersonic speeds (~ mach 2) whereat the parachute is released. During this phase, the vehicle flies a guided entry approach to reduce position errors at parachute deploy. The guidance algorithm minimizes the down-range and cross-range errors by changing the lift vector through bank angle commands. [3]

The Entry Controller provides attitude control of the entry capsule during the exo-atmospheric and atmospheric phases using Reaction Control System (RCS) thrusters. During the exo-atmospheric phase it detumbles the entry capsule and orients it to its desired entry attitude. During the atmospheric phase it tracks guidance bank angle commands, damps aerodynamic oscillation modes while minimizing fuel usage.

The Entry Controller has feedforward and feedback paths. The feedforward path allows for a fast tracking response to large bank angle commands. The feedback path uses a Proportional-Differential (PD) controller with attitude and rate deadbands. The deadbands are chosen such that the vehicle is stabilized about its unforced trim attitude, in order to efficiently damps oscillation modes and tracks bank commands. This is achieved by using large attitude deadbands and small rate deadbands. The large attitude deadbands provide robustness against uncertainty in the vehicle trim position knowledge. This is especially critical because fuel is limited and it is undesirable to spend fuel trying to change the vehicle's unforced trim attitude. The small rate deadbands enable damping of oscillatory modes and maintaining stability. The parameters of the Entry Controller are tabulated to allow for different gain settings at different flight regimes. The Entry Controller commands are implemented by pulse width modulation of the RCS thruster.

The Viking landers used a similar approach back in the seventies. They flew a lift-up trajectory and used a 3-axis entry attitude controller with RCS thrusters [4-6]. In addition, phase plane design techniques and RCS pulse width

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modulation have been extensively studied and applied to many space missions as discussed in [7] and references therein.

The Entry Controller design of the Mars Science Laboratory has gone through some earlier designs using a phase plane approach without feedforward [8] and an LQR approach. This paper describes the current Entry Attitude Controller concept and shows some preliminary simulation results.

II. Objectives

The objective of the Entry Controller is to provide 3-axis attitude control during the exo-atmospheric and entry phases of EDL. During the exo-atmospheric phase the capsule will separate from the cruise stage, de-spin and perform a turn to the predicted desired entry attitude, and hold that attitude. This phase lasts about 9 minutes. The entry phase starts when the sensed acceleration reaches a given threshold. The entry phase finishes at the parachute deploy at about mach 2.

For the Exo-atmospheric phase the Entry Controller needs to

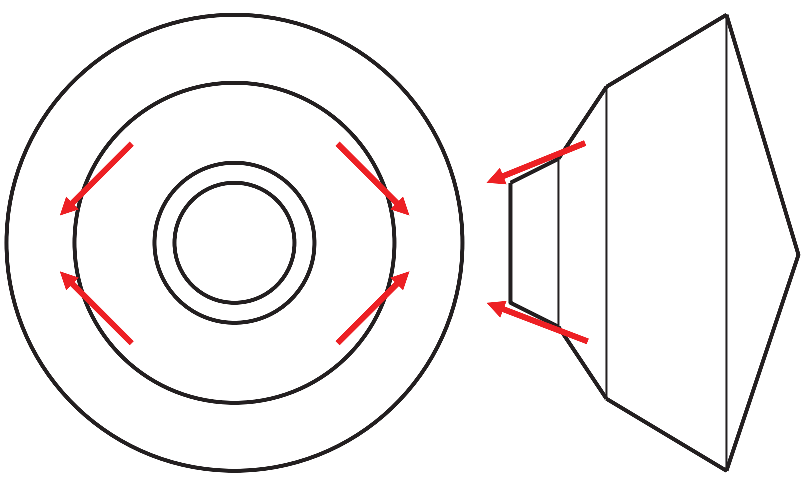
a. De-spin the descent stage
b. Turn to desired attitude for entry in the martian atmosphere. That is, align the capsule to the predicted trim angle of attack and the initial bank angle expected by the entry guidance algorithm.
c. Maintain 3 axis attitude hold.

For the Entry phase, the Entry Controller needs to

d. Stabilize 3 axis attitude by maintaining the actual Angle of Attack within a deadband about the Predicted Trim Angle of Attack (function of Mach number) and maintaining the Sideslip within a deadband about the predicted sideslip angle which is zero.
e. Track the Entry Guidance bank angle commands.

In addition, the Entry Controller should keep the fuel consumption for both phases to be less than 15Kg. 80% of this allocation will be employed for performing bank reversals commanded by the entry guidance algorithm. The remaining 20% is used for attitude hold. This allocation is comparable to the fuel used by the Viking Landers during the coast and entry phase (1.6 and 2.1 kg) [6].

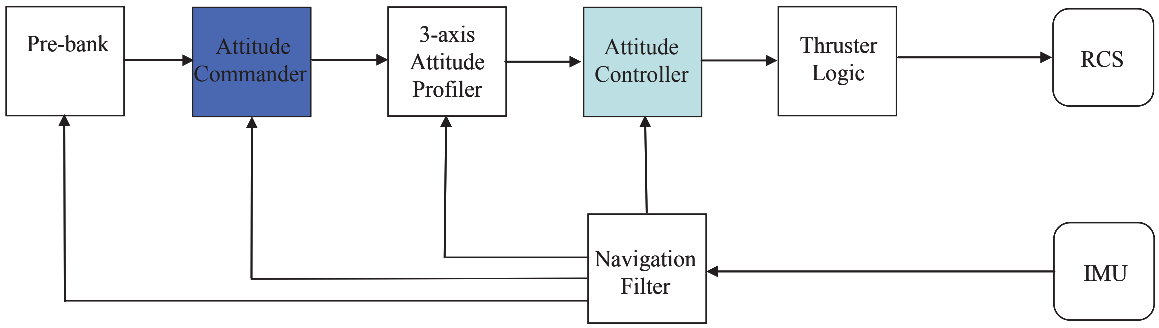
An on-board navigation filter integrates accelerometer and gyro data from an Inertial Measurement Unit (IMU) to provide position and attitude state estimates for the Entry Controller. The configuration of the RCS thrusters is depicted in Figure 1. At each thruster location, there is a pod with two thrusters. There are a total of 8 RCS thrusters.



Figuere 1. RCS Thrusters

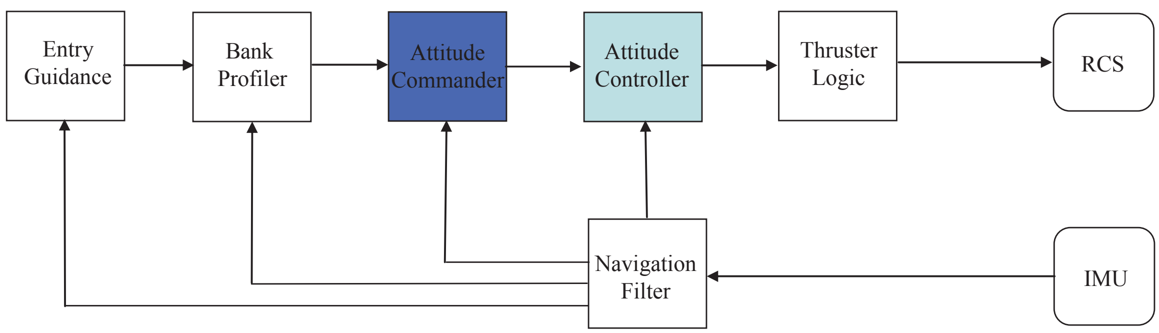
III. FUNCTIONAL DIAGRAMS

The exo-atmospheric control and entry control functional diagrams are shown in Figures 2 and 3 respectively.



Figuere 2. Exo-atmospheric phase functional diagram

Exo-atmospheric phase: the Attitude Commander block generates the desired attitude in two steps: A pitch rotation by the current predicted trim angle of attack; and a roll rotation by the desired intial bank angle, denoted as Pre-bank. The 3-Axis Attitude Profiler generates the profile to take the entry capsule to that state. In doing so, it first nulls the angular rates and then it profiles a turn to the desired attitude. The Attitude Controller takes state information from the onboard Navigation Filter and the desired attitude from the 3-axis attitude profiler to generate the control errors. It calculates the desired torques to zero the control errors. The Attitude Controller is a gain scheduled controller. The parameters are read from a parameter table which is indexed by the estimated atmospheric relative speed. The attitude controller will be further described in the following section. The Thruster Logic block provides a pulse-width-modulation implementation of the attitude controller desired torques.



Figuere 3. Entry phase functional diagram

During the entry phase, the Entry Guidance algorithm, which is derived from the Apollo command module final phase guidance algorithm and adapted to Mars entry, generates bank angle commands to control range-to-go and cross-range errors by adjusting the drag acceleration. [3]. When the cross-range errors exceed a given threshold the Entry Guidance algorithm will command a bank reversal. These reversals are large turns and therefore are profiled by the Bank Profiler, which plans a single axis accelerate-coast-decelerate attitude maneuver.

IV. Entry Attitude Controller Description

The entry capsule approximates a biconic vehicle. During the entry phase a CG-offset is used to create a lift to drag (L/D) ratio of approximately 0.24, which leads to a trim angle of attack of about -15.5 degrees at entry interface and varies slightly over time. The Entry Controller calculations are performed in a Control Frame which is defined as a non-orthogonal frame depicted in Figure 4. The yaw (x-axis) and pitch (y-axis) correspond to eigenvectors of the aerodynamic oscillatory modes. The roll (z-axis) corresponds to the bank angle. This definition allows deadband settings around the dynamic variables of interest. Yaw and pitch deadbands are sized for rate damping of oscillatory modes. Bank deadband is sized for guidance performance.

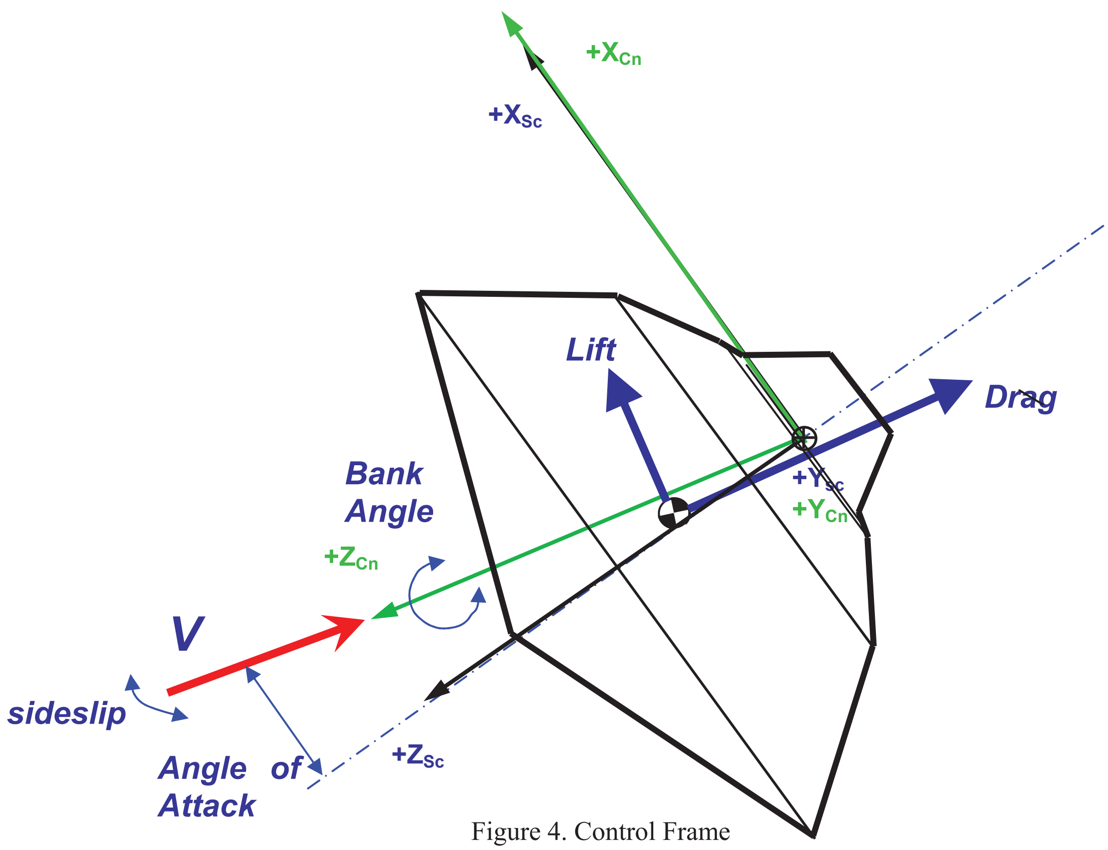


Figure 4. Control Frame

This Control Frame is time varying since the vehicle's trim angle of attack varies over the trajectory. The predicted trim angle of attack for a representative trajectory is shown in Figure 5. The predicted trim sideslip angle is nearly zero. These angles are derived from the MSL aerodynamic database developed by NASA's Langley Research Center [9]. Uncertainty in the predicted values needs to be accounted in choosing the attitude deadbands. The Viking project observed a 2 degrees discrepancy between the predicted and actual angles of attack values [6] for both flights. In addition, the aerodynamics oscillatory mode frequency (short period, dutch roll) changes over the trajectory.

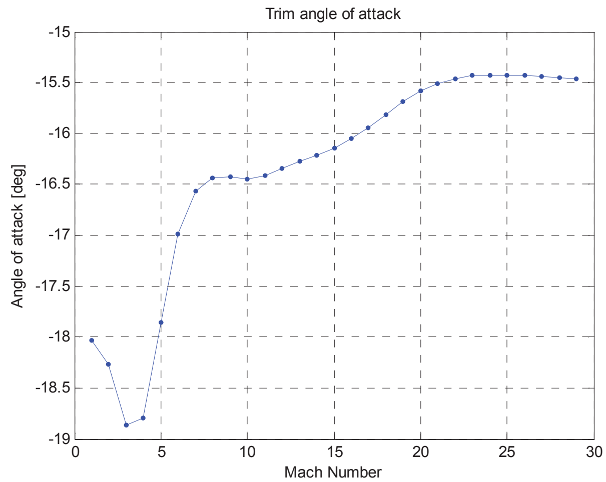


Figure 5. Predicted Trim Angle of Attack.

The separation of the lateral and longitudinal aerodynamics, in conjunction with formulating the control problem in the Control Frame, enables the parameterization of the Entry Controller as three independent channels.

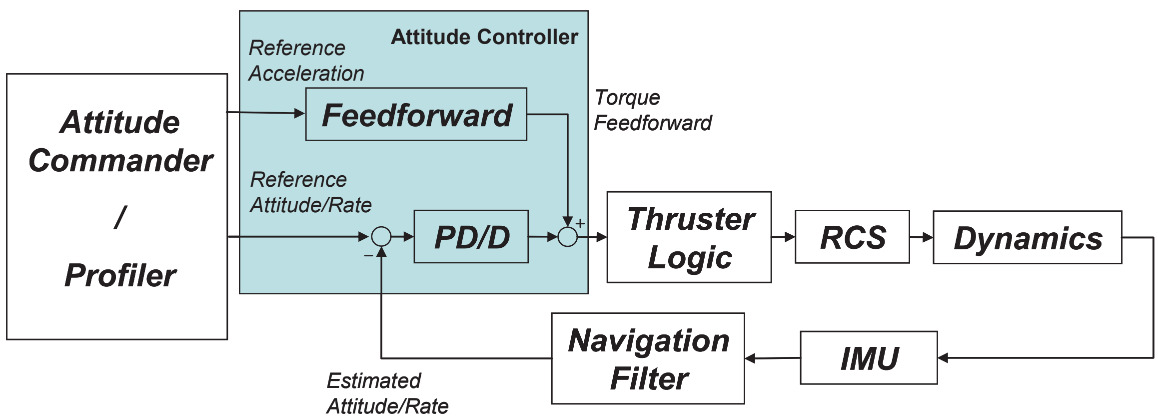


Figure 6. Single axis controller structure

The structure of the controller for each channel has a feedback and a feedfoward path as shown in Figure 6. The feedforward path is used to achieve a fast response during large turns. The feedback path is used to stabilize the plant. The feedback path has a PD/D controller with attitude and rate deadbands to minimize fuel usage. A phase plane representation is given in figure 7. The attitude and rate errors are computed relative to the deadbands. Crossing the deadband engages the feedback gradually and therefore it is expected that the errors will surpass the deadbands.

The controller gains and deadbands are tabulated for different flight regimes and different events. During the exoatmospheric phase, the attitude deadbands are set large in order to minimize fuel during limit cycling. Just before entry, the attitude deadbands are tightened up to reduce disturbance effects. During the entry phase, the attitude deadbands are set large and the rate deadbands small. This enables the feedback to behave primarily as a rate control. It provides both energy damping and robustness against knowledge errors in the predicted trim angle of attack. Both of the Viking vehicles trimed at about 2 degrees higher negative angles than predicted [6]. Error in the predicted trim angle of attack is an important factor in the selection of the attitude deadbands when trying to minimize the fuel usage. Attitude deadbands need to be large enough to accommodate for trim prediction errors. Too small attitude deadbands in face of prediction errors will cause the controller to fight the actual trim angle of attack and result in large fuel consumption. For the same reason, the Viking landers flew a rate damping controller during the entry phase [6]. For MSL, the attitude deadbands are tightened up again before parachute deploy to reduce the initial attitude error and the subsequent dynamic disturbance during chute deploy.

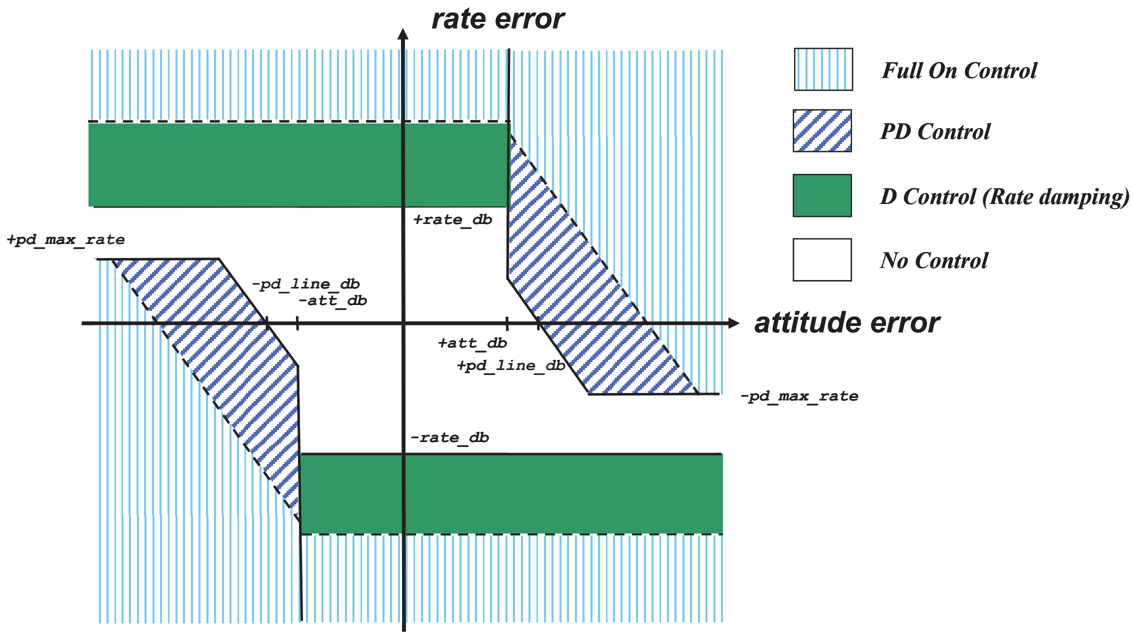


Figure 7. Feedback path phase plane (PD/D)

Stability analysis of the Entry Controller with nonlinear effects and representative time delays shows that this controller provides a sufficient gain (>10 dB) and phase margins (>30 deg) for the different flight regimes, including the worst case pitch dynamic instability effects [10]. In addition, a low pass filter in the feedback path rolls off the gain at high frequencies and decouples the controller from the structural flexible modes. Figure 8 shows the Nichols chart for the bank channel for a linearized model of the aerodynamics which includes the effects of slosh and the dominant structural flexible modes.

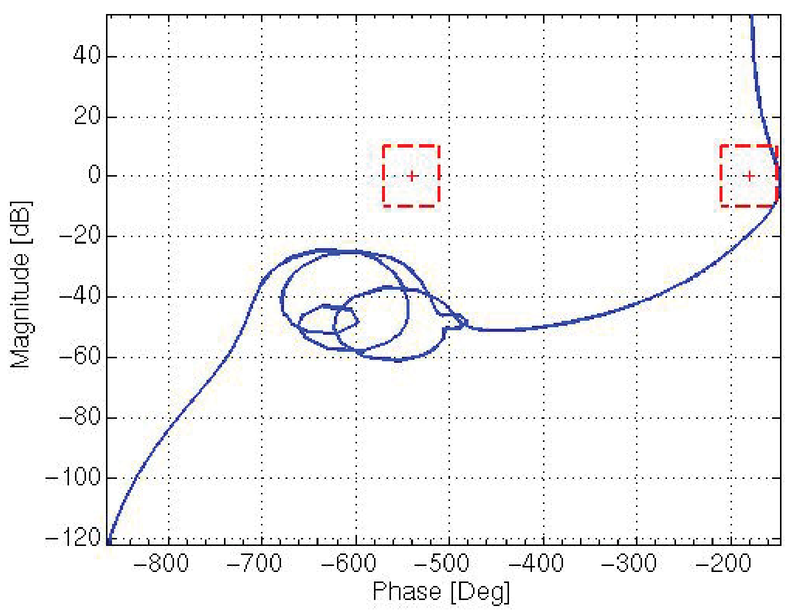


Figure 8. Nichols chart.

V. Simulation Example

This section shows a detail simulation example. The simulation was executed in the Control Analysis Simulation Testbed (CAST) which is a JPL developed computer simulation testbed for EDL. This testbed has models for the environment (gravity, aerodynamics, etc.) and for the spacecraft dynamics, sensors (IMU) and actuators (RCS). In addition, it calls the Guidance, Navigation, and Control (GN&C) algorithms as implemented in actual flight software. First, we will describe the behavior during the exo-atmospheric phase. Section A describes the spin-down and turn-to-entry, and section B the exo-atmospheric attitude hold. Then, we will show the atmospheric entry phase in section C. Figure 9 shows the GNC mode versus time. This mode provides information on the on-going GN&C activities. The simulation was set to start at time equal to 1000 s. The spin-down and turn-to-entry spans from 1000 s. to 1022 s. The exo-atmospheric attitude is in attitude-hold as wait-for-entry mode lasts from 1022 s to 1600 s. The entry phase starts at 1600s and ends at 1778 s.

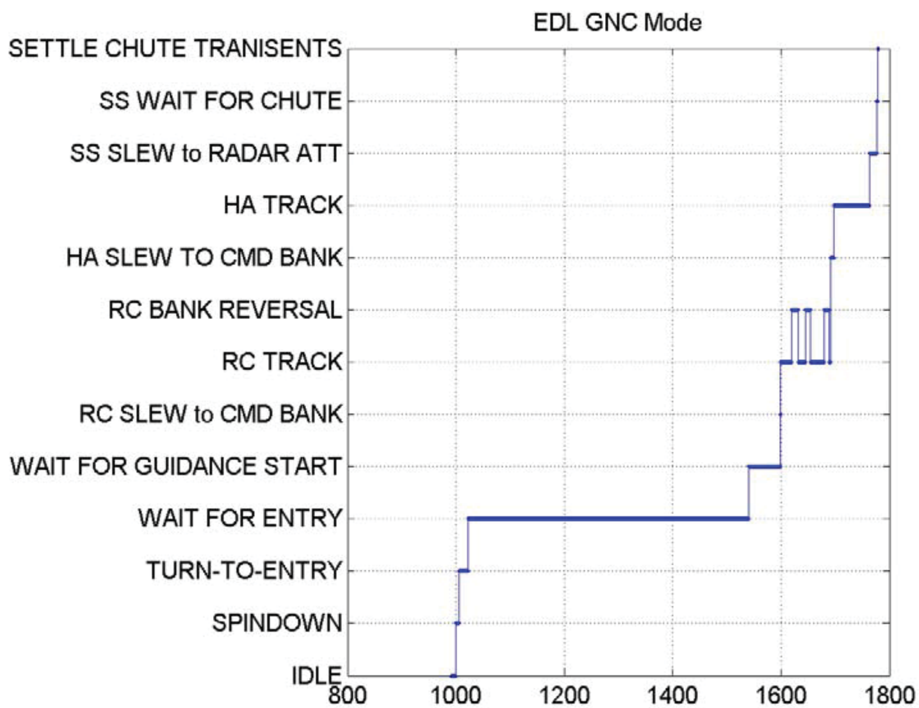


Figure 9. Entry Descend and Landing (EDL) Guidance Navigation and Control (GNC) Mode

A. Spin-down and turn-to-entry

The MSL cruise stage is a spinner. Therefore, once the entry capsule separates from the cruise stage, the entry capsule will transit to 3 axis attitude control. The first activity is to spindown the capsule which is rotating at 12 deg/s and then turn to the desired entry attitude. This is illustrated by the GN&C mode in Figure 10. The turn attitude consists of the predicted trim angle of attact and sideslip angle at contact with the Mars atmosphere, and the initial bank angle command selected by the Guidance algorithm. As mentioned earlier, large turns are profiled using the feedforward path. The achieved rates can be seen in Figure 11. The attitude errors and rate errors are plotted in Figures 12 and 13 respectively. And the desired torque commands and RCS thruster commands in Figures 14 and 15.

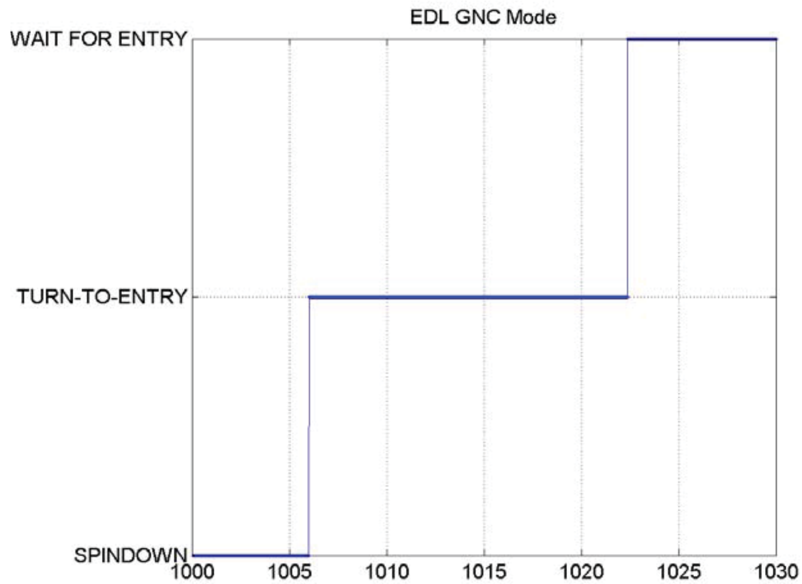


Figure 10. Entry Descend and Landing (EDL) Guidance Navigation and Control (GNC) Mode

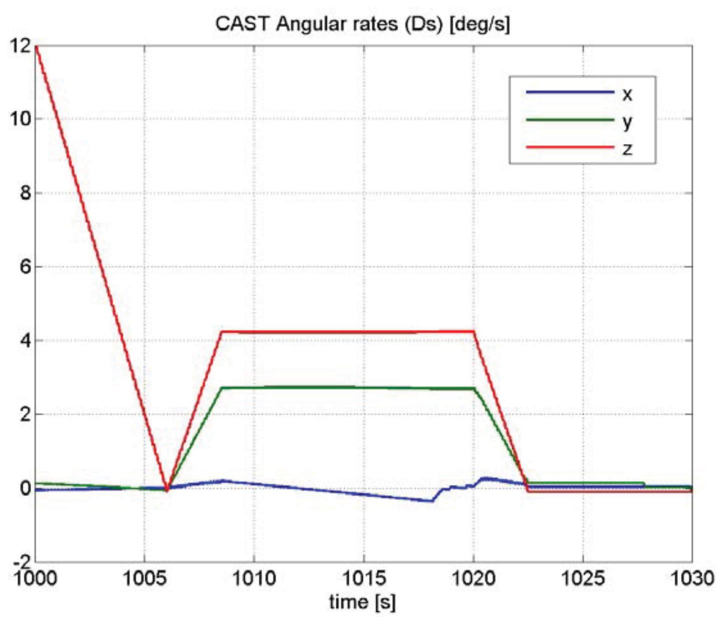


Figure 11. Capsule actual angular rates.

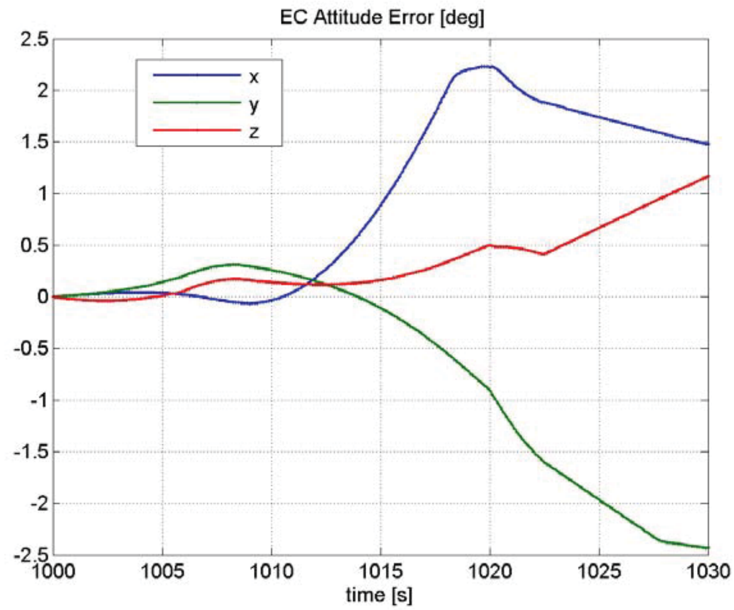


Figure 12. Entry Controller Attitude Error

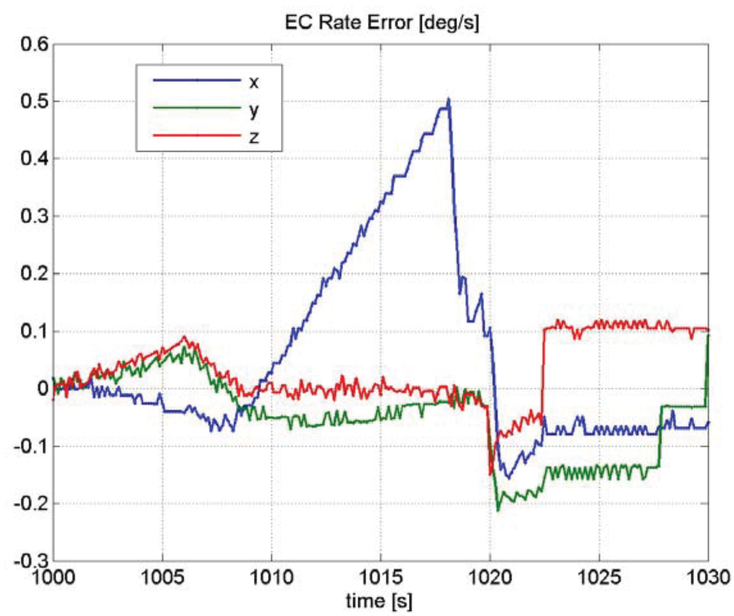


Figure 13. Entry Controller Rate Error

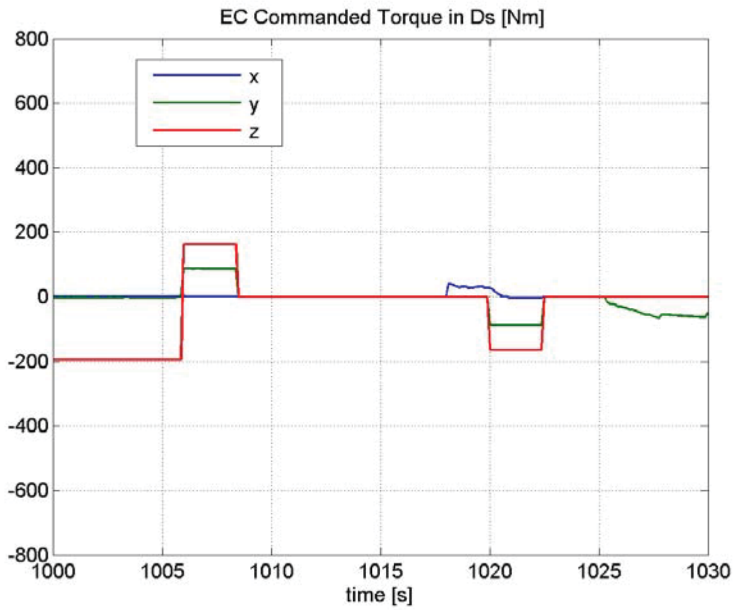


Figure 14. Entry Controller Commanded Torque.

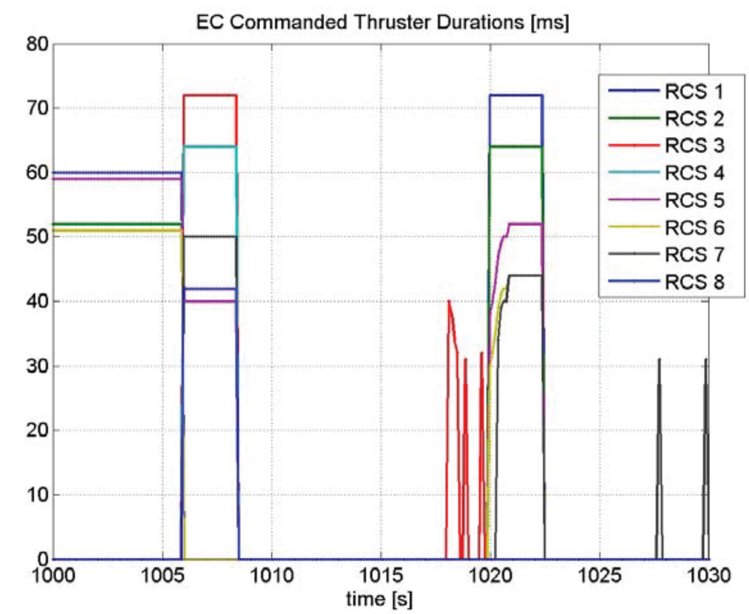


Figure 15. Entry Controller Commanded Thruster Durations.

B. Exo-atmospheric attitude hold

The corresponding plots for the exo-atmospheric attitude hold phase are shown. The expected behavior is to basically limit cycles about the 2 degree attitude deadbands, which is nicely illustrated in the phase plane plots in Figure 19.

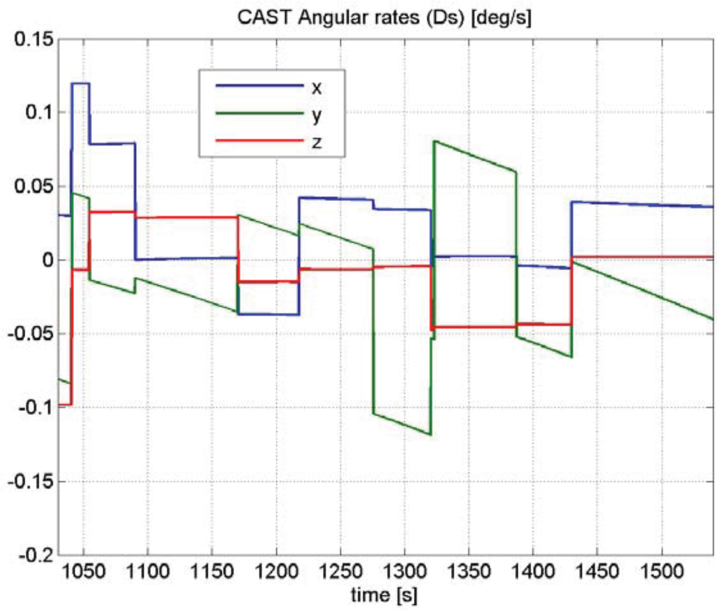


Figure 16. Capsule actual angular rates.

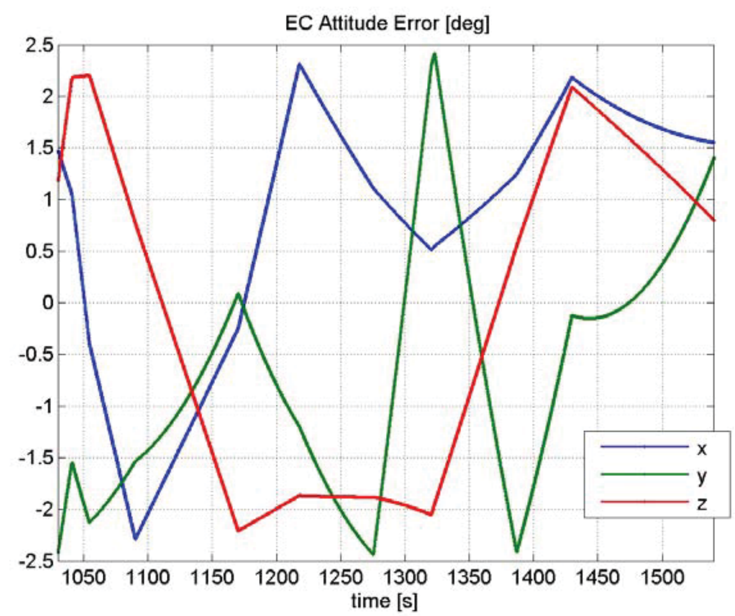


Figure 17. Entry Controller Attitude Error

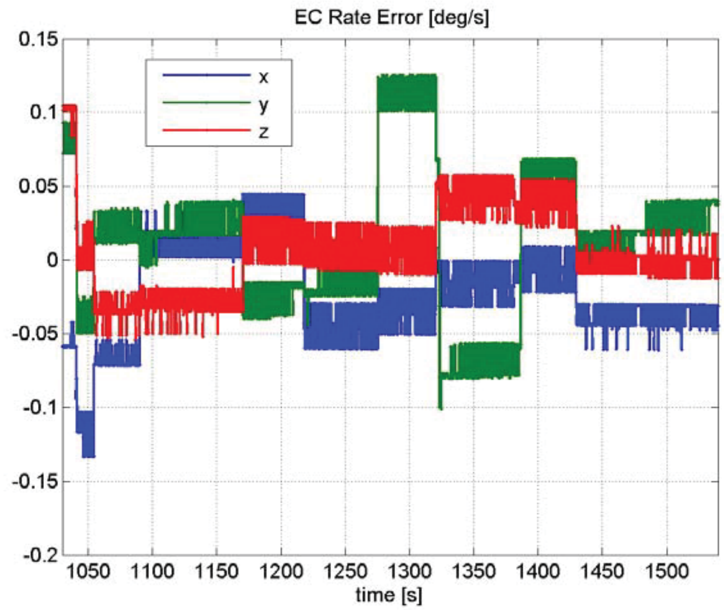


Figure 18. Entry Controller Rate Error

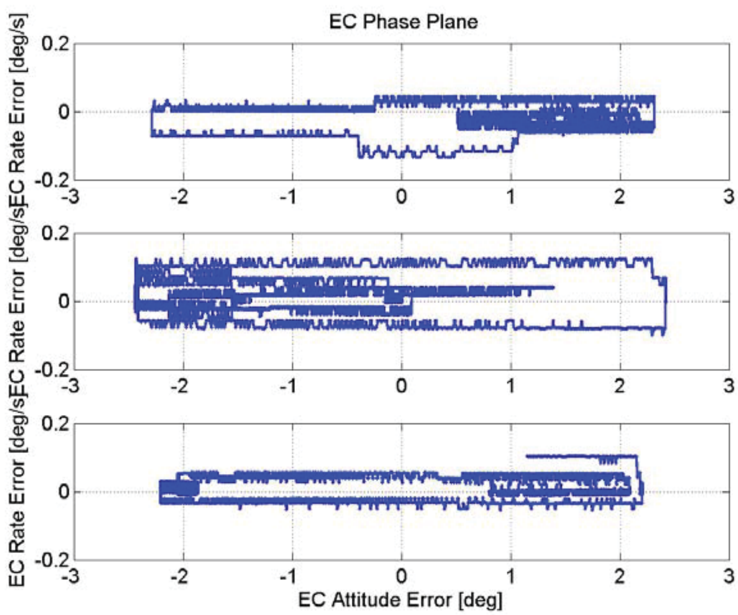


Figure 19. Entry Controller Phase Planes for Yaw, Pitch and Bank channels (top to bottom)

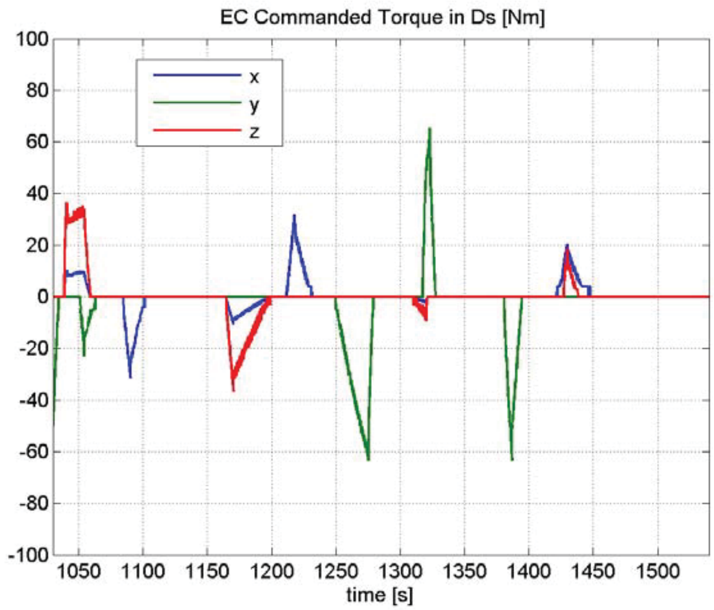


Figure 20. Entry Controller Commanded Torque.

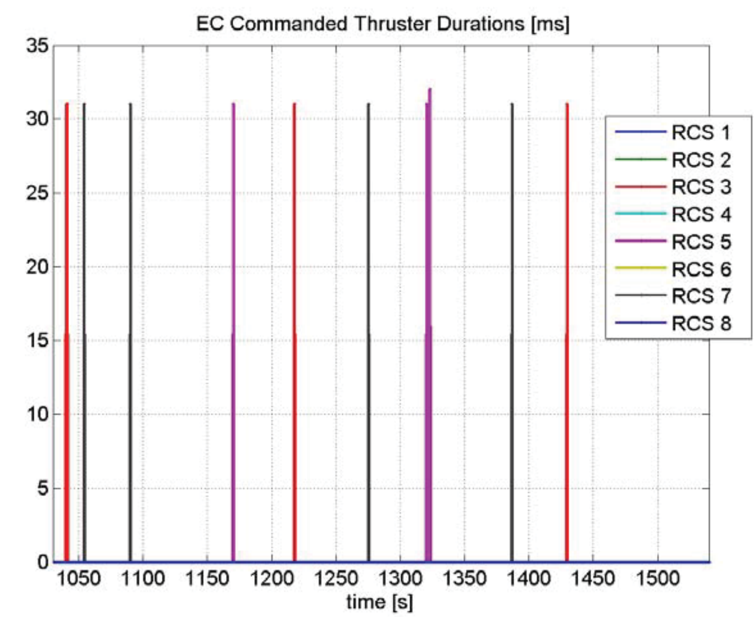


Figure 21. Entry Controller Commanded Thruster Durations.

C. Atmospheric Entry Phase

The activities happening during the atmospheric phase are summarized in the EDL GNC mode, Figure 22. It starts at the *Wait for Guidance start* mode, where it waits until the sensed drag acceleration reaches a given threshold. In the simulation test case, it occurred at 1598s. At this point the Entry Guidance algorithm is called for the first time and generated the first bank angle command. The bank profiler will then profile a turn to take the bank angle from the pre-bank used during the exo-atmospheric phase to the new bank command, denoted as *RC Slew to Cmd Bank* mode. Then, it goes into *RC Track*, where the guidance algorithm tracks the downrange errors. When the cross-range errors get too large, it commands a bank reversal and the mode toggles to *RC Bank Reversal.* When the heading alignment phase starts, the bank profiler plans a turn to the first heading alignment bank angle, as *HA Slew to Cmd Bank,* and goes into *HA Track.* Before the chute opens a roll slew is performed to point the radar antennas to the ground, denoted as *SS Slew to Radar Att.* At the same time the CG-offset is removed by ejecting 6 balance masses. Once the slew is complete, it goes into *SS Wait for Chute,* where it waits for the right conditions to open the parachute. When this conditions are met the entry attitude controller is disabled and the GNC mode goes into *Settle Chute Transients.* Figure 23 shows the bank angle time histories. It illustrates the bank profiles during the slews and bank reversals. The corresponding profiled bank acceleration and rate is shown in Figure 26. Figure 24 shows the predicted and actual angles of attack. It shows a small mismatch between the predicted and the actual. Figure 25 shows the sideslip angle. Both angle and attack and sideslip angle shows aerodynamic induced oscillations. Figure 27 shows the actual spacecraft rates. Figure 28 and 29 show the attitude and rate errors. Figure 30 shows the phase plane. Figure 31 and 32 shows the attitude control desired torques and the commanded RCS thruster durations.

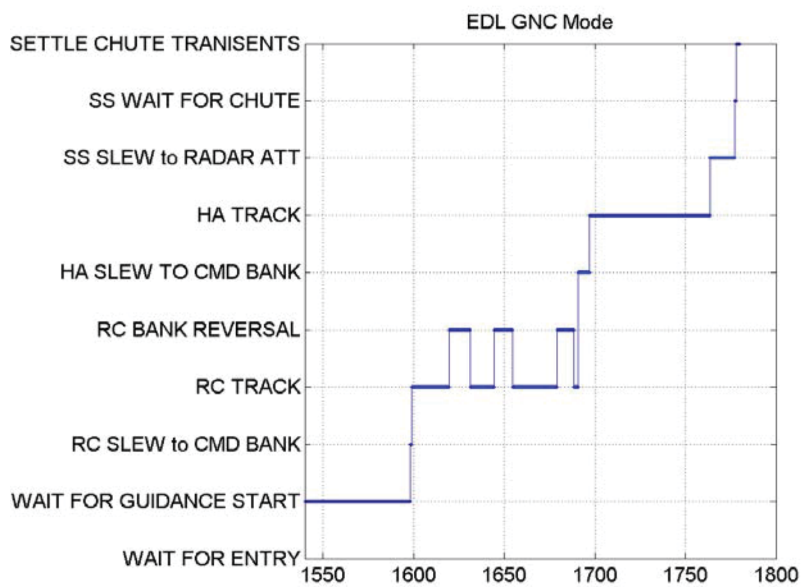


Figure 22. Entry Descend and Landing (EDL) Guidance Navigation and Control (GNC) Mode

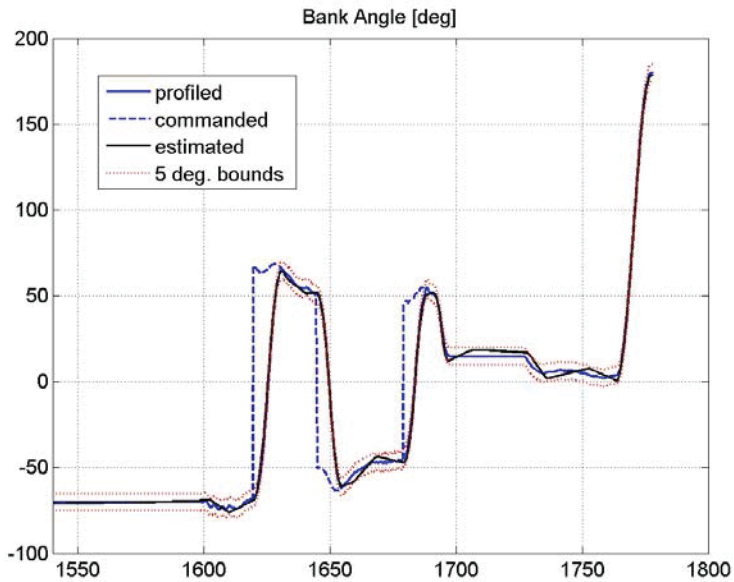


Figure 23 Bank Angle

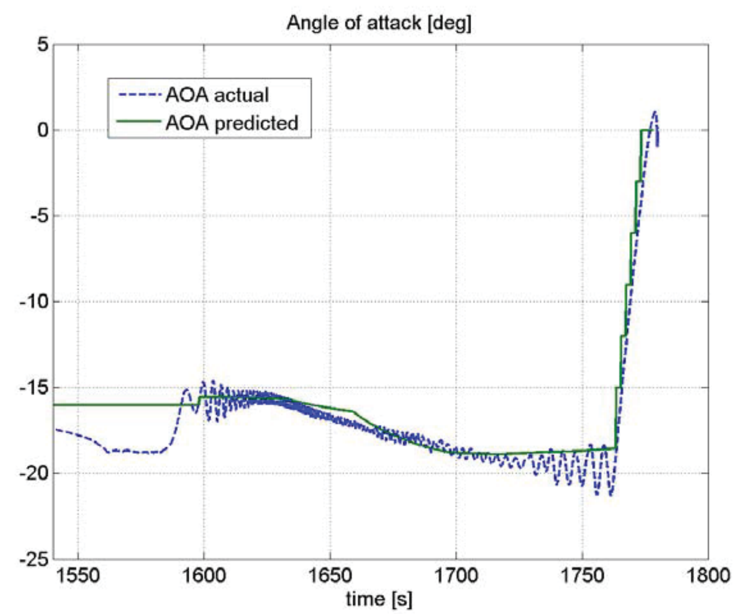


Figure 24. Angle of Attack predicted and actual

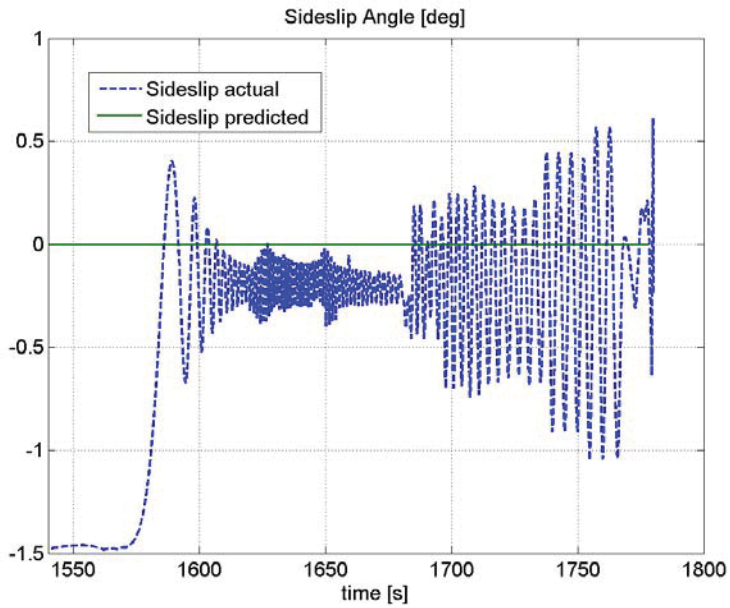


Figure 25. Sideslip Angle predicted and actual

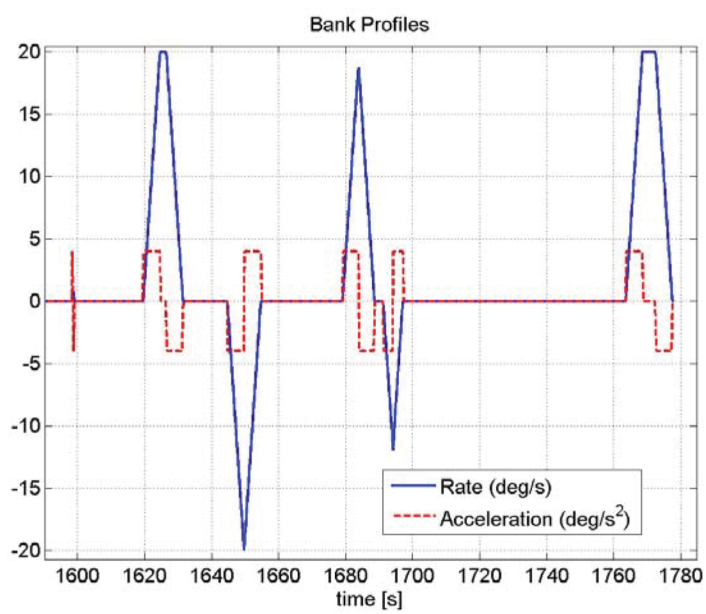


Figure 26. Acceleration and rates profiled and feed-forwarded.

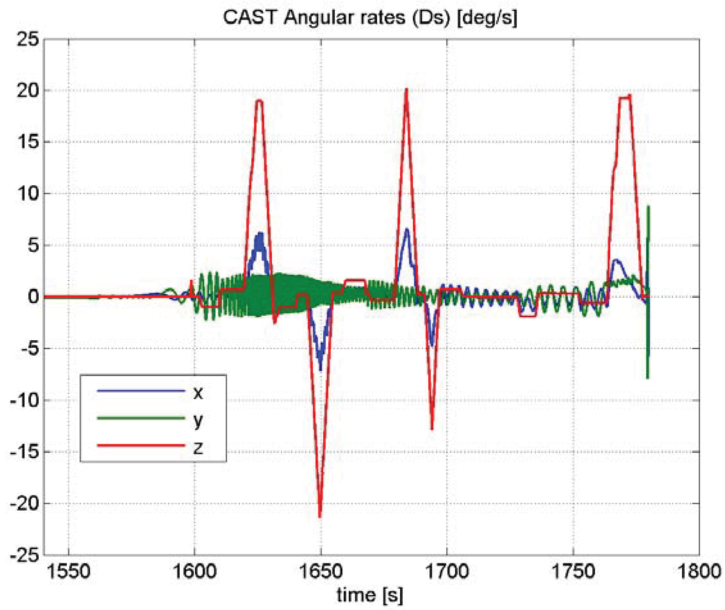


Figure 27. Capsule actual angular rates.

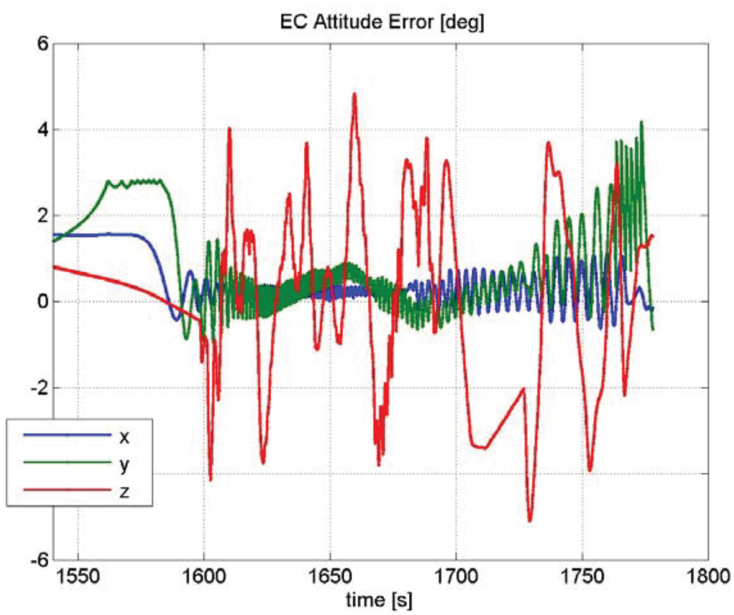


Figure 28. Entry Controller Attitude Error

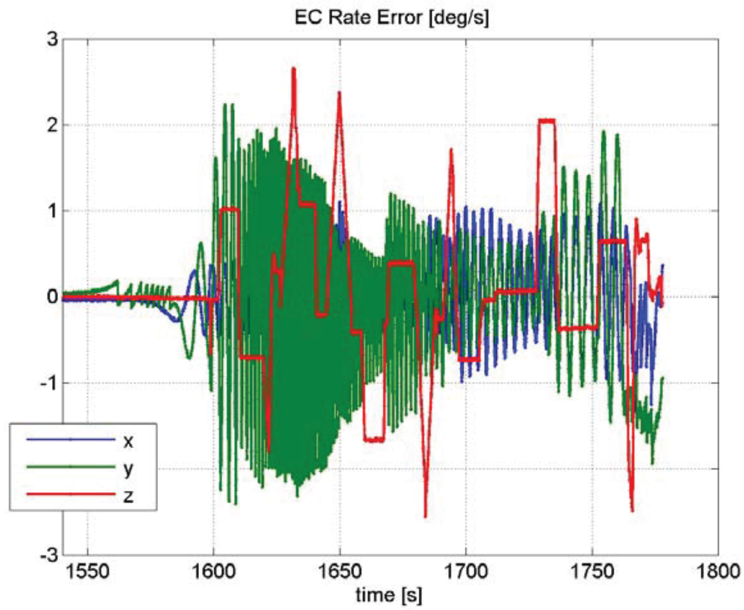


Figure 29. Entry Controller Rate Error

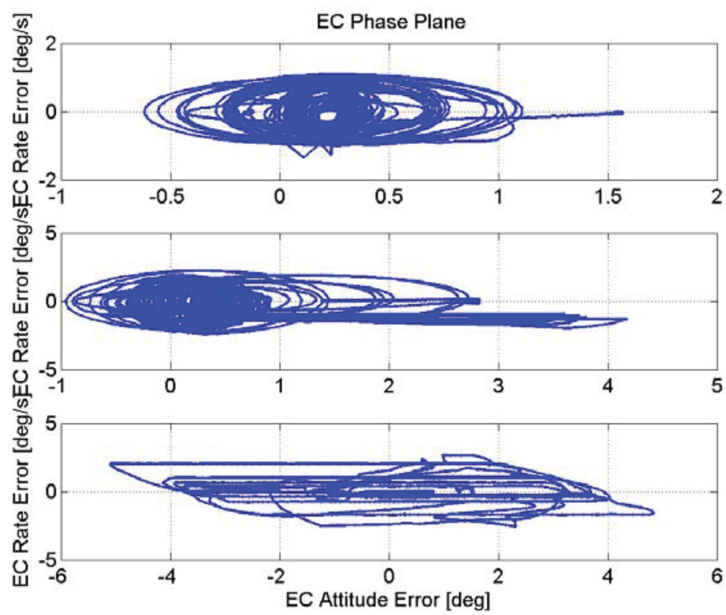


Figure 30. Entry Controller Phase Planes for Yaw, Pitch and Bank channels (top to bottom)

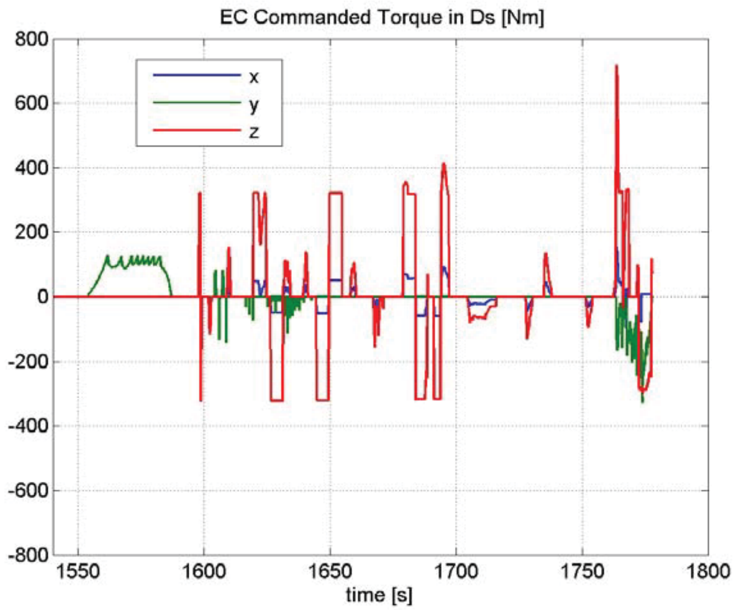


Figure 31. Entry Controller Commanded Torque.

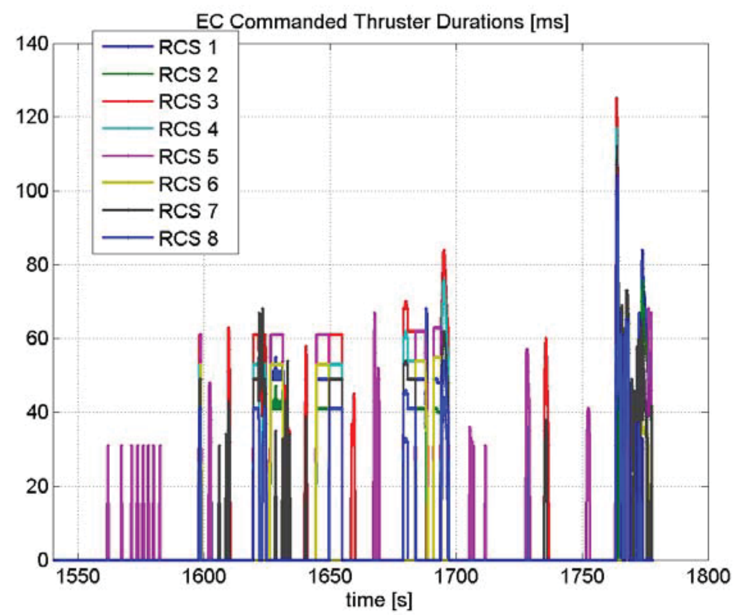


Figure 32. Entry Controller Commanded Thruster Durations.

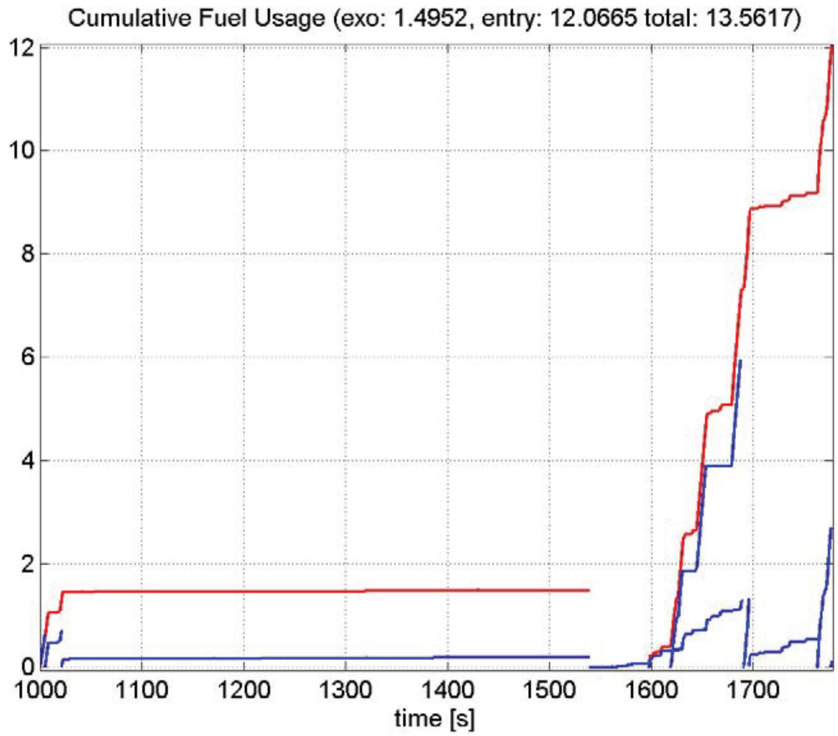


Figure 33. Fuel Usage per phase (red) and per mode (blue)

Figure 33 shows the cumulative fuel consumption. The blue curves show the usage at each GNC mode. The red curves sums up the use for the exo and entry phases.

VI. Conclusions

This paper presented the concept for the Attitude Controller for the Atmospheric Entry phase of the Mars Science Laboratory Entry, Descend and Landing. The controller is parameterized as 3 independent channels around the predicted trim position. Each channel controller is composed of a feedfoward and a feedback path. The feedforward path enables fast response to large bank commands. The feedback path stabilizes the plant around attitude and rate deadbands while minimizing fuel usage. Feasibility and the satisfactory performance of this design have been demonstrated by computer simulations.

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