Entry Attitude Controller for the Mars Science Laboratory

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Abstract [1] [2]— This paper describes the preliminary concept for the RCS 3-axis attitude controller for the exo-atmospheric and guided entry phases of the Mars Science Laboratory Entry, Descend and Landing. 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. 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 structure with deadbands that minimizes fuel usage. The performance of this design is demonstrated via simulation.

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1. INTRODUCTION

This paper describes the preliminary 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. The attitude control during the power descent phase of EDL is performed in conjunction with the trajectory control and it is discussed in [1]. An overview of the EDL system and its challenges is presented in [2].

The exo-atmospheric phase starts after separation from the Cruise stage to contact with 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 RCS thrusters. During the exo-atmospheric phase it detumbles the entry stage 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 is formulated in the stability frame. It has feedforward and feedback paths. The feedforward path allows for a fast tracking response to large bank angle commands. The feedback path uses a PD controller with attitude and rate deadbands. The deadbands are chosen such that the vehicle is stabilized about its unforced trim attitude, 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.

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[2] IEEEAC paper #1500, Version 3, Updated December 8, 2006

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 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.

2. REQUIREMENTS AND OBJECTIVES

The key requirements and objectives of the entry controller are:

(1) During the Exo-atmospheric segment to (i) de-spin the descent stage and (ii) turn to entry and maintain attitude by aligning the S/C trim axis with atmospheric relative velocity and setting the initial bank angle desired by the entry guidance, and maintaining 3 axis attitude hold with a 5 degrees deadband.

(2) During the Entry segment to (i) stabilize attitude by maintaining the actual Angle of Attack within a dead-band about the Predicted Trim Angle of Attack (function of Mach number) and maintaining the Sideslip within a dead-band about zero angle and (ii) track the Entry Guidance bank angle commands.

(3) 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 sub-allocation is comparable to the fuel used by the Viking Landers during the coast and entry phase (1.6 and 2.1 kg) [6].

3. FUNCTIONAL DIAGRAM

The Entry Controller provides 3 axis attitude control during the exo-atmospheric and entry phases of EDL. It receives state information from the onboard Navigation Filter and commands from the Guidance algorithm, and generates jet firing commands to the RCS system. The entry functional diagram is given in Figure 1.

The Entry Guidance is derived from the Apollo command module final phase guidance algorithm and adapted to Mars entry. The guidance commands a bank angle to control range-to-go and cross-range errors by adjusting the drag acceleration. [3]. The Navigation Filter provides position and attitude estimates from propagating the Inertial Measurement Unit (IMU) data.

The Attitude Profiler calculates the desired attitude and rate profiles for large bank angle commands. The profile is a single axis accelerate-coast-decelerate attitude maneuver in the roll axis. However, during the exo-atmospheric segment, the detumble and turn to entry are performed using a 3 axis profiler in an inertial frame. The Reference Attitude 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 bank angle.

The Attitude Controller calculates the RCS thrusters' commands to track guidance commands and stabilize the capsule around the predicted trim angle of attack and sideslip. 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 next section. The Thruster Logic block provides a pulse width modulation implementation of the attitude controller desired torques.

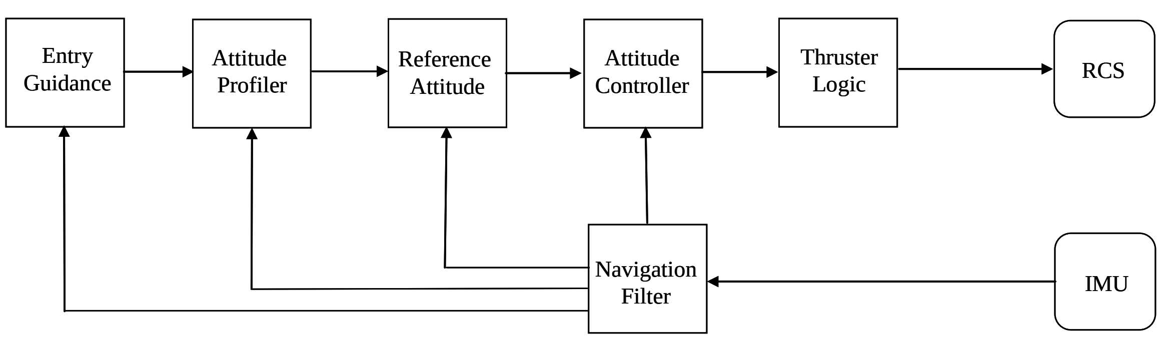

Figure 1. Entry Functional Diagram

4. Attitude Controller Description

The entry capsule approximates a biconic vehicle. During the entry phase a CG-offset is used to create an L/D ratio of approximately 0.24, which leads to a trim angle of attack of about -16 degrees. The Entry Controller calculations are performed in a Control Frame which is defined to match the predicted location of the aerodynamic stability frame. This Control Frame is time varying since the vehicle's trim angle of attack varies over the trajectory. Attitude errors in this frame correspond to angle of attack, sideslip and bank angle errors.

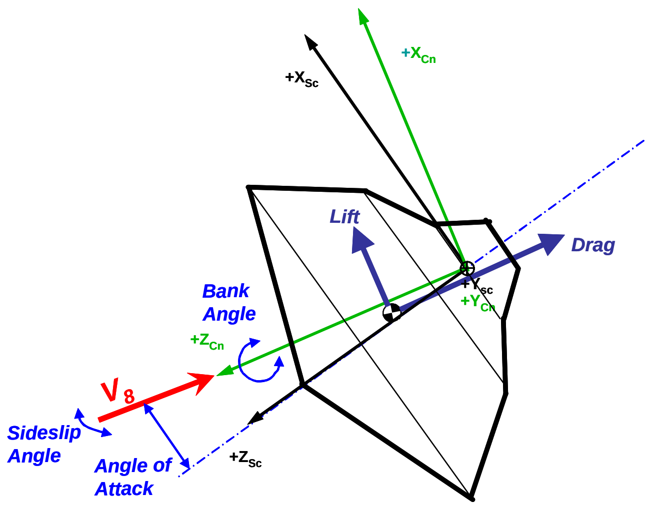

Figure 2. Control Frame

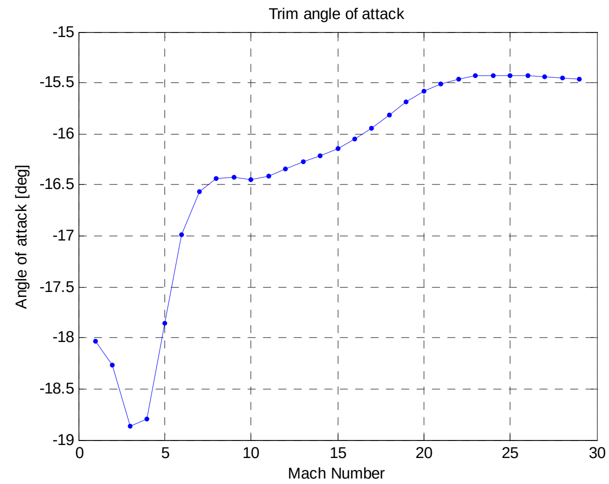

Figure 3. Predicted Trim Angle of Attack.

The dynamic behavior is dominated by aerodynamic effects. The predicted trim angle of attack for a representative trajectory is shown in Figure 3. The predicted trim sideslip angle is 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 modes (short period, dutch roll) change frequency over the trajectory. 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.

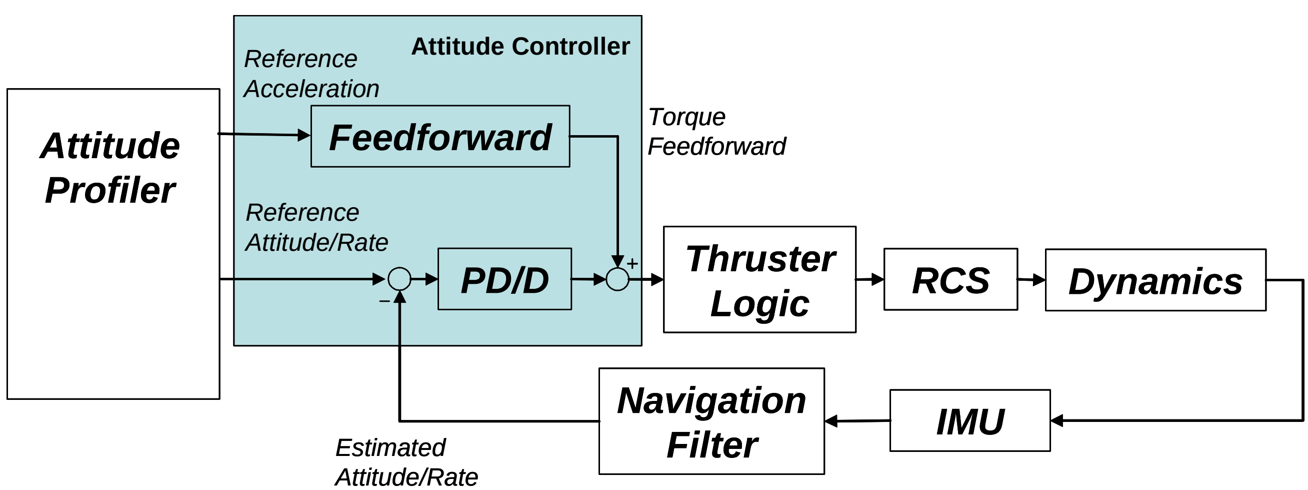

Figure 4. Attitude Controller Diagram

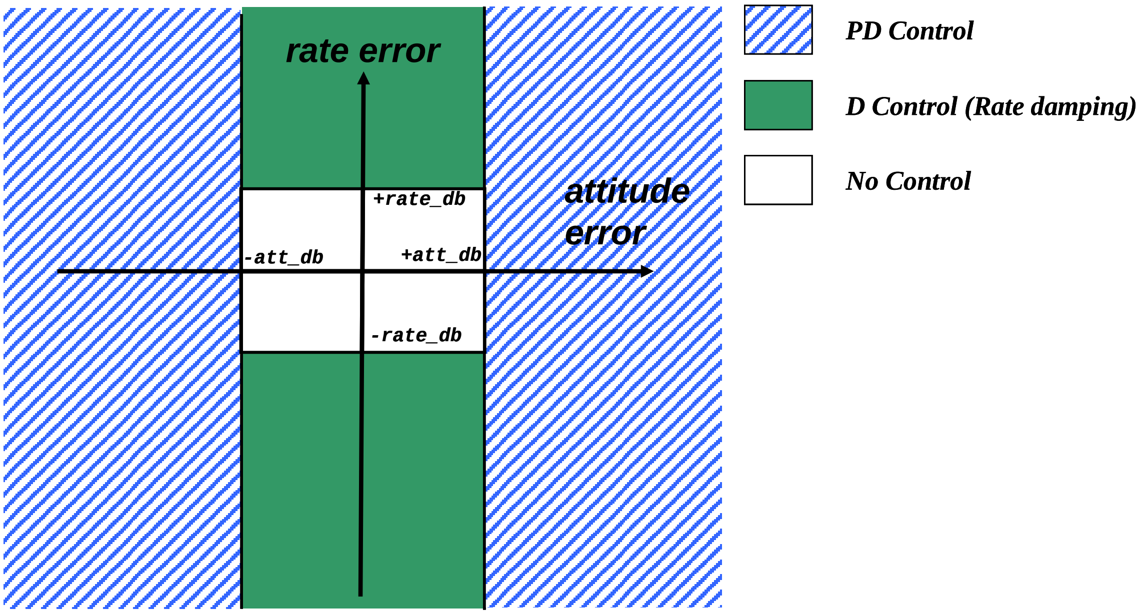

Figure 5. Attitude Controller Feedback Logic and Deadbands

The structure of the controller for each channel has a feedback and a feedfoward paths as shown in Figure 4. 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 5. The attitude and rate errors are 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 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 segment, the attitude deadbands are set large and the rate deadbands small. This makes 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 lead the controller to fight the actual trim angle of attack and cause large fuel consumption. For the same reason, the Viking landers flew a rate damping controller during the entry phase [6]. For MSL, before parachute deploy the attitude deadbands are tightened up again to reduce disturbances and meet interface requirements.

Preliminary stability analysis of the entry controller with simplified aerodynamics and representative time delays shows that this controller provides a sufficient gain (>6 dB) and phase margins (>30 deg) for the different flight regimes, including the worst case pitch dynamic instability effects [10].

5. SIMULATIONS

This section shows some preliminary simulation results. We present a simulation test case for an entry lift up trajectory (zero bank angle command) with attitude deadbands set to 2 deg and rate deadbands set to 0.5 deg/s. It corresponds to an initial error at entry interface of 3 deg in sideslip and 2.5 deg and in angle of attack. In addition, it includes the worst case dynamic instability predicted in [10]. Figure 6 shows the attitude errors. Note that the angle of attack drifts during the trajectory due to errors in the predicted trim angle of attack, as expected it does not trip the angle deadband. We can also observe the limit cycling in the bank angle. Figure 7 shows the attitude rate errors. Figure 8 shows the corresponding phase plane plot (attitude vs rate). As it was explained in section 4, the control torque engages gradually as the attitude or rate errors pass their deadband values causing the attitude or rate errors to overpass the deadband values. And Figure 9 shows the cumulative fuel consumption. This number is representative of what will be used in flight for attitude maintenance during the entry phase.

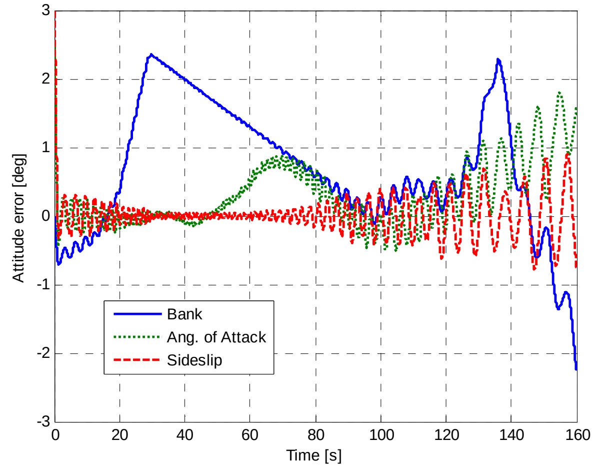

Figure 6. Attitude Error (deg) vs. Time (sec)

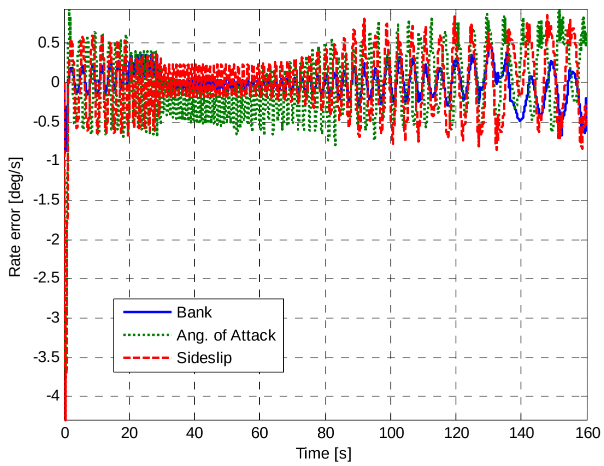

Figure 7. Rate Error (deg/s) vs. Time (sec)

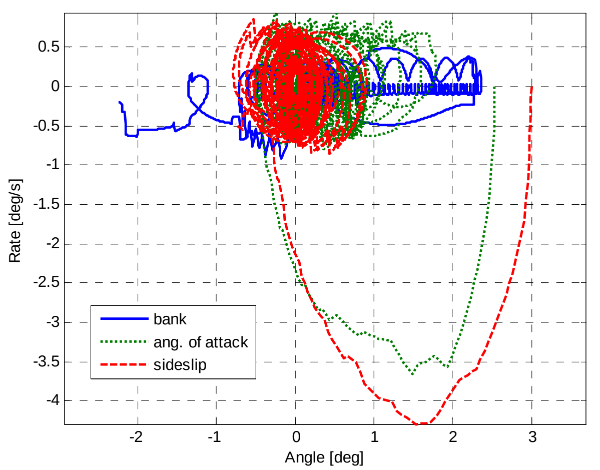

Figure 8. Phase plane.

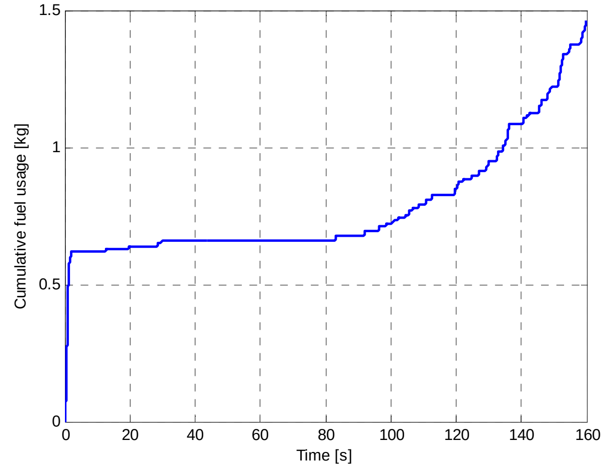

Figure 9. Cumulative fuel usage (kg) vs. Time (sec)

6. CONCLUSIONS

The preliminary concept for the entry attitude controller for the Mars Science Laboratory Entry, Descend and Landing has been presented. 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. Simulation results show the feasibility of this design.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Dr. Paul B. Brugarolas is a senior engineer at the Jet Propulsion Laboratory. He received the Electrical Engineer degree from the University of Navarre, San Sebastian, Spain, and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Southern California, Los Angeles, CA. He joined the Guidance and Control Analysis Group at the Jet Propulsion Laboratory in 1997. He has been involved in the application of modern control and estimation techniques to a wide range of emerging spacecraft and missions, including the Spitzer Space Telescope, the Shuttle Radar Topography Mission, the Cassini Mission, and research and technology developments for optical instruments and for exploration of asteroids and comets. He is currently designing the entry attitude controller for the Mars Science Laboratory. His research interests include robust control, estimation theory, system identification and model validation. He received the NASA Exceptional Achievement Medal for contributions to the Shuttle Radar Topography Mission. He is a senior member of the IEEE and AIAA

Miguel San Martin received his B.S. Degree in Electrical Engineering with honors from Syracuse University in 1982, and his M.S. Degree in Aeronautics and Astronautics Engineering from the Massachusetts Institute of Technology in 1985. He joined the Jet Propulsion Laboratory in 1985. His area of interest is the analysis, design, implementation, and testing of spacecraft articulation and attitude control systems, with an emphasis on applied estimation theory. He has participated in several flight projects and has been a member of numerous flight anomaly tiger teams. He was the designer of the Cassini spacecraft Attitude Estimator, the TOPEX/Poseidon Altimeter pointing calibration ground software, and was the technical lead for the Mars Pathfinder Attitude Control Subsystem flight software. More recently he was the Guidance and Control System Manager and Chief Engineer for the Mars Exploration Rover Project, which successfully landed the Spirit and Opportunity rovers in January 2005. He is currently the Guidance Navigation and Control System Chief Engineer for the Mars Science Laboratory project. He has received two NASA Exceptional Achievement Medals for contributions to the Mars Pathfinder and the Mars Exploration Rovers Missions.

Dr. Edward C. Wong is a Principal Engineer and Technical Group Leader in guidance and control design and analysis at the Jet Propulsion Laboratory. He graduated from UCLA and has worked in many advanced studies and flight projects such as the Voyager, Galileo, Cassini, Space Station Payload Pointing, Infra-Red Telescope Facility, Shuttle Radar Topography Mission, Mars Rendezvous and Sample Return studies, Autonomous Rendezvous Experiment, and Mars Science Laboratory. He is primarily responsible for the design, development, and validation of control algorithms in both flight and ground software. His primary fields of interest are spacecraft attitude control and determination, system identification, autonomous rendezvous and entry, descent, and landing. He has taught Numerical Analysis in the UCLA Extension, and is a member of IEEE, Sigma Xi, and Tau Beta Pi. He has received NASA's Exceptional Service Medal and New Technology Awards.