Numerical Optimization on Approach and Landing for Reusable Launch Vehicle

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Abstract: The development of a plane which can fly to space at lower cost, which is reusable and can take more payloads, is very much required for further development of space industries. The Reusable Launch Vehicle, usually called Spaceplane or Hyperplane which can take crew and payload into orbit is being developed by various space agencies and private companies. The Spaceplane would make space travel cheap and will help in increasing space tourism and just like in the aviation industry, within a few decades, the space tourism industries would be worth billions. The objective of this paper is to design a numerically optimized trajectory on approach and landing phase of Reusable Launch Vehicle.

Keywords: Quasi Equilibrium Glide; RLV; Numerical Optimization; Approach and Landing

1. Introduction

Second generation (and future generation) RLVs may eventually take the place of the space shuttles, but not before scientists perfect the technologies that make RLVs safer, more reliable, and less expensive than the shuttle fleet. To achieve this goal, a variety of RLV trajectory design approaches have recently been proposed. Generally, an RLV mission is composed of four major flight phases: ascent, re-entry, terminal area energy management (TAEM), and approach and landing (A&L).

A neural network has been employed for optimal trajectories over the flight conditions in A&L, from which the trajectory to be flown can be reshaped to improve on range flown [1]. Another algorithm was developed for A&L by iteratively seeking to satisfy a final-flare flight-path-angle constraints [3]. An Autolanding trajectory design for the X-34 Mach 8 vehicle was presented in Barton and Tragesser (1999). The techniques facilitate rapid design of reference trajectories. The trajectory of the X-34 based on the shuttle approach and landing design was from steep glideslope, circular flare, and exponential flare to shallow glideslope.

The objective of this paper is to develop new approaches that can deliver an RLV to its landing site safely and reliably, recover the vehicle from some failures, and avoid mission abort as much as possible and hence to generate trajectory of an unpowered RLV by implementing numerical optimization during A&L phase of reentry

2. System Model

2.1 Point-mass Equations of Motion

For an unpowered RLV during A&L, the discussion is restricted only to flight in the longitudinal plane. The gliding flight in a vertical plane of symmetry is then defined by the following point mass equations

\[ \dot{V} = \frac{m}{M} - g \sin \gamma \]

\[ \dot{\gamma} = \frac{1}{M} \frac{m}{V} - \frac{g}{V} \cos \gamma \]

\[ \dot{h} = V \sin \gamma \]

Energy height is the total mechanical energy of the vehicle divided by its weight.

Here we select energy height as independent variable for integration instead of time

\[ e = \frac{V^2}{2g} + h \]

2.2 Aerodynamic Model

The lift and drag forces are

\[ L = \bar{q} S C_L \]

\[ D = \bar{q} S C_D \]

Where \( \bar{q} \) is dynamic pressure, \( S \) is wing surface area, \( C_L \) and \( C_D \) are lift and drag coefficients. Dynamic pressure is

\[ \bar{q} = \frac{1}{2} V^2 \]

Where \( \rho \) is atmospheric density. Lift and drag coefficient is defined as

\[ C_L = C_{L0} + C_{La} \alpha \]

\[ C_D = C_{D0} + C_{KL} L^2 \]

Where \( C_{L0} \) is coefficient at zero angle of attack, \( C_{D0} \) is zero-lift drag coefficient, \( K \) is induced-drag coefficient, and \( C_{La} \) is “lift slope” coefficient.

\[ \frac{L}{D} = \frac{C_L}{C_D} = \frac{C_{L0}}{C_{D0} + K C_L^2} \]
Angle of attack for maximum L/D can be now found by substituting $C_a^*$ for $C_a$

$$a^* = \frac{C_a^* - C_{a0}}{C_{1a}} \quad (17)$$

### 2.3 Control Model

Given that the purpose of this research is to develop a means of computing a control profile that maximizes the range covered by the vehicle, several possible approaches have been considered for defining the control profile. The only control input considered in this study is angle of attack and, to simplify the model, the dynamics of the control system are neglected—i.e., adjustments in angle of attack are assumed to take place instantaneously. In reality, angle of attack cannot be adjusted instantaneously because it is controlled by ailerons that require time to move and because the vehicle requires time to respond to the new control input. The assumption of instantaneous control is adequate, however, for observing basic trends in optimal control profiles, even if those profiles are not continuous or differentiable. A non-differentiable control profile cannot be achieved in reality (where velocity, acceleration, and higher-order rates must all be continuous), but a differentiable curve might be fitted to approximate the non-differentiable profile with little effect on performance of the vehicle. It is assumed that a realistic control system could nearly replicate the control profiles found in this study by use of such an approximation. Hence, the dynamics of the control system are neglected for the purposes of this investigation.

Optimal control profiles should closely resemble the maximum-L/D trajectory, which is derived as a simple approximation of the optimal trajectory. In order to highlight the differences between flying at max L/D and flying an optimal trajectory, the original control profile definition was modified so that each control node was defined as a deviation $\delta a(t)$ from $a^*$

$$a(t) = a^*(M) + \delta a(t) \quad (18)$$

It was believed that the optimal angle of attack at a given instant was primarily affected by Mach number, so the control nodes were parameterized in terms of Mach number instead of time

$$a(M) = a^*(M) + \delta a(M) \quad (19)$$

Mach number was not guaranteed to be monotonic, and because the flight dynamics are integrated with respect to energy height, it was finally decided that the control nodes should be parameterized in terms of energy height, which is monotonic:

$$a(e) = a^*(M) + \delta a(e) \quad (20)$$

### 3. Numerical Optimization

The optimization problem is defined as follows: Find the $\delta a(e)$ profile that minimizes

$$F = -R(e_f) \quad (21)$$

where $R(e_f)$ is the horizontal range flown when the vehicle has reached the final energy height, \( e_f \), and the $\delta a(e)$ profile is defined according to Eq. (20). The value of at each control node, then, serves as one independent variable in the optimization problem. Equation (21) gives the negative of $R(e_f)$ for use with the MATLAB fmincon function because fmincon only minimizes objective functions, and the purpose of this optimization is to maximize $R(e_f)$. In order for the terminal states of the trajectory to coincide with the A&L interface, it is possible to set one or more terminal-state equality constraints:

$$C_1(e_f) = V(e_f) - V_f = 0 \quad (22)$$
$$C_2(e_f) = \gamma(e_f) - \gamma_f = 0 \quad (23)$$
$$C_3(e_f) = h(e_f) - h_f = 0 \quad (24)$$
Figure 1: Altitude Vs. energy height for case1

Figure 2: Angle-of-attack Deviation Vs. energy height for case1

Figure 3: Range Vs. energy height for case1

Figure 4: Velocity Vs. energy height for case1

Figure 5: Altitude Vs. energy height for case2

Figure 6: Angle-of-attack Deviation Vs. energy height for case2

Figure 7: Range Vs. energy height for case2
5. Conclusion

A higher-order interpolation method might also improve the realism of the control profile by making it more feasible to employ with real control surfaces, given that real control surfaces cannot respond instantly to control commands. For that matter, it might be helpful to include the pitch control dynamics of the vehicle in the simulation model, rather than assuming the vehicle can adjust its angle of attack instantaneously. These unmodeled details could affect the optimization of the control profile. Along with other methods of interpolating between control nodes, it may be desirable to consider non-uniform distributions of nodes along the trajectory, placing more nodes in areas needing higher resolution (e.g., at energy heights for which velocity is transonic), improving the range of the vehicle without the computational expense of increasing the number of control nodes.
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References


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