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TRAJECTORY OPTIMIZATION FOR THE NATIONAL AEROSPACE PLANE

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1. Introduction

While continuing the application of the inverse dynamics approach in obtaining the optimal numerical solutions, the research during the past six months has been focused on the formulation and derivation of closed-form solutions for constrained hypersonic flight trajectories. Since it was found in the research of the first year that a dominant portion of the optimal ascent trajectory of the aerospace plane is constrained by dynamic pressure and heating constraints, the application of the analytical solutions significantly enhances the efficiency in trajectory optimization, provides a better insight to understanding of the trajectory and conceivably has great potential in guidance of the vehicle.

Work of this period has been reported in four technical papers (Refs. [1]–[4]). Two of the papers were presented in the AIAA Guidance, Navigation, and Control Conference (Hilton Head, SC, August, 1992) and Fourth International Aerospace Planes Conference (Orlando, FL, December, 1992). The other two papers have been accepted for publication by *Journal of Guidance, Control, and Dynamics*, and will appear in 1993. The following briefly summarizes the work done in the past six months and work currently underway. The details can be found in Refs. [1]–[4]

2. Analytical Solutions of Constrained Flight

In many flight control and trajectory optimization problems, certain portions of the trajectory are required to follow some state space constraints dictated by operational or safety considerations. The optimal aerospace plane ascent trajectory, for instance, has a portion of 60% – 80% lie on the dynamic pressure and heating constraints ([1]-[2]). A complete analytical characterization of the constrained part of the trajectory will provide an efficient mean to evaluate the trajectory, and often lead to a better understanding of the trajectory. In turn, tasks such as trajectory optimization, control and guidance can be significantly simplified.

The flight trajectory of aerospace vehicles subject to a class of path constraints has been studied. The analysis reveals that under some fairly general conditions the altitude dynamics and flight path angle dynamics constitute a natural two-time-scale system: the flight path angle dynamics is fast and the altitude dynamics slow. The approximate asymptotic solution for the flight path angle is given as a function of the altitude from which the velocity can be expressed as an explicit function of time, regardless of the specific forms of the constraints. If the altitude can be solved in terms of the velocity from the constraint, both the altitude and the flight path angle have analytical expressions as functions of time [3]. The dynamic pressure and heating rate constraints to which the aerospace plane is subject are in the class of constraints discussed. With this development, only the initial climbout and final zoom into orbit need to be numerically investigated. The dominant midcourse of the trajectory is represented by analytical formulas. Thus the trajectory optimization is dramatically simplified. Figure 1 shows the comparison of the optimal trajectory generated numerically and the trajectory obtained using analytical solutions. Despite the visible difference in the flight times, the fuel consumptions are very close.

The use of closed-form solutions is not limited to trajectory optimization. Another important application is the hypersonic cruise trajectory design. Given the requirements on the cruise trajectory such as holding an almost constant altitude and flying at maximum lift-to-drag ratio, the cruise trajectory can be shown to satisfy an algebraic constraint of the class discussed. The a complete characterization of the cruise trajectory as explicit functions of time can be obtained ([3]). Figure 2 shows the comparison of a numerically generated cruise trajectory and a trajectory defined by closed-form formulas. The cruise speed is about Mach 15 and the altitude 40 km. The two trajectories are almost indiscernible.

3. Guidance Laws Using Inverse Dynamics Approach.

The inverse dynamics approach in trajectory optimization was first employed for this research (Refs. [1–2], [5]). The main advantage is that the conditioning of of the optimization problem is greatly improved. With this approach, the very difficult trajectory optimization problem for the aerospace plane can be solved. Extensive numerical experiments have been conducted in the first phase of this research. Another interesting application of the inverse dynamics approach in guidance has also been investigated during the past six months. The idea is to use this approach to linearize the nonlinear dynamics without actually linearization with respect to the controls. Since the nominal optimal trajectory has already been generated via inverse dynamics, no extra heavy computation will be involved if the guidance laws are used onboard. The result is that the error in tracking the nominal trajectory is governed by a stable second-order system, and the errors approach zero asymptotically [2]. Figures 3 and 4 show the comparison of the altitude and flight path angle histories on the actual and nominal trajectories for an initial altitude error of $\Delta h_0 = 1$ km and flight path angle error of $\Delta\gamma_0 = 4°$.

4. Work Under Investigation

(1). Since we already have a relatively good understanding of the optimal trajectory in 2-D case, work is underway to study 3-D optimal ascent trajectories. More state variables and controls are involved in 3-D maneuvers. The inverse dynamics approach is still expected to have an essential role in obtaining a 3-D optimal trajectory.

(2). In the early stage of flight testing of an aerospace plane, it is critical to be prepared for abort mission. This research will investigate optimal aerodynamic controls for the aerospace plane for maximum-range landing trajectories in all direction (footprint).

(3). Although it is not clear at this point whether the aerospace plane will have limited thrust vectoring control (TVC) capability, this study will investigate whether or not significant fuel-consumption reduction can be achieved if TVC is available.

(4). Given the complexity and technical challenges in the design of an aerospace plane, a multidisciplinary design approach that encompasses key areas of traditional design has been recognized as a necessity. But less emphasis is given to a trajectory/vehicle design approach. Since the aerospace plane will have to fly a very stringent trajectory, a simultaneous design of optimal trajectory and vehicle may yield significant improvement in the overall system. Efforts will be made to demonstrate this possibility by considering some simplified trajectory/vehicle design problems.

References

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[3] Lu, P., "Analytical Solutions to Constrained Hypersonic Flight Trajectories", to appear in *Journal of Guidance, Control, and Dynamics*, 1993.

[4] Lu, P., and J. Samsundar, "Closed-Form Solution of Constrained Trajectories: Application in Optimal Ascent of Aerospace Planes", Fourth International Aerospace Planes Conference, Orlando, FL, Dec. 2–4, 1992.

[5] Lu, P., "Trajectory Optimization for the National Aerospace Plane", Annual Report, NASA grant No. NAG-1-1255, June, 1992.

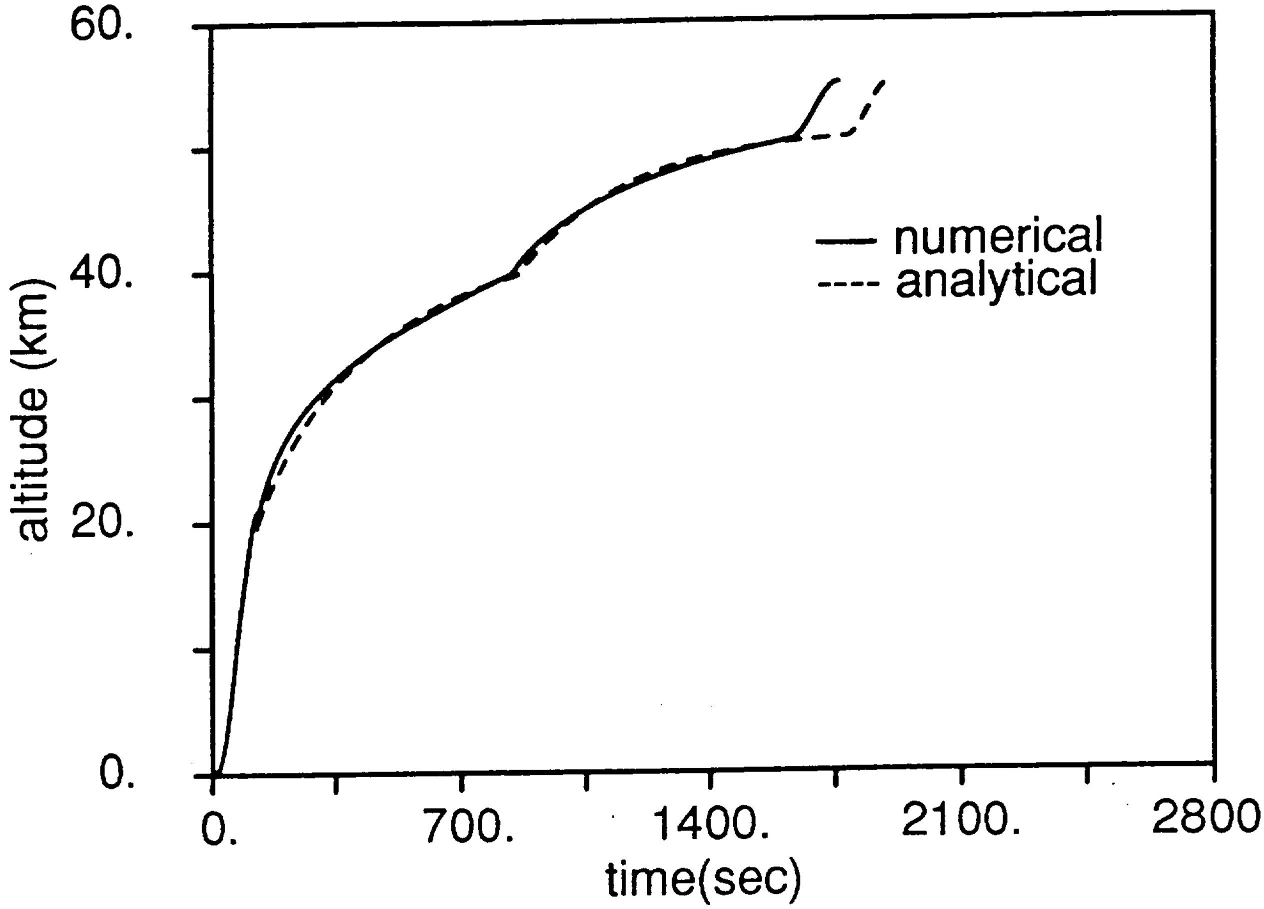

Figure 1. Comparison of numerical and analytical ascent trajectories

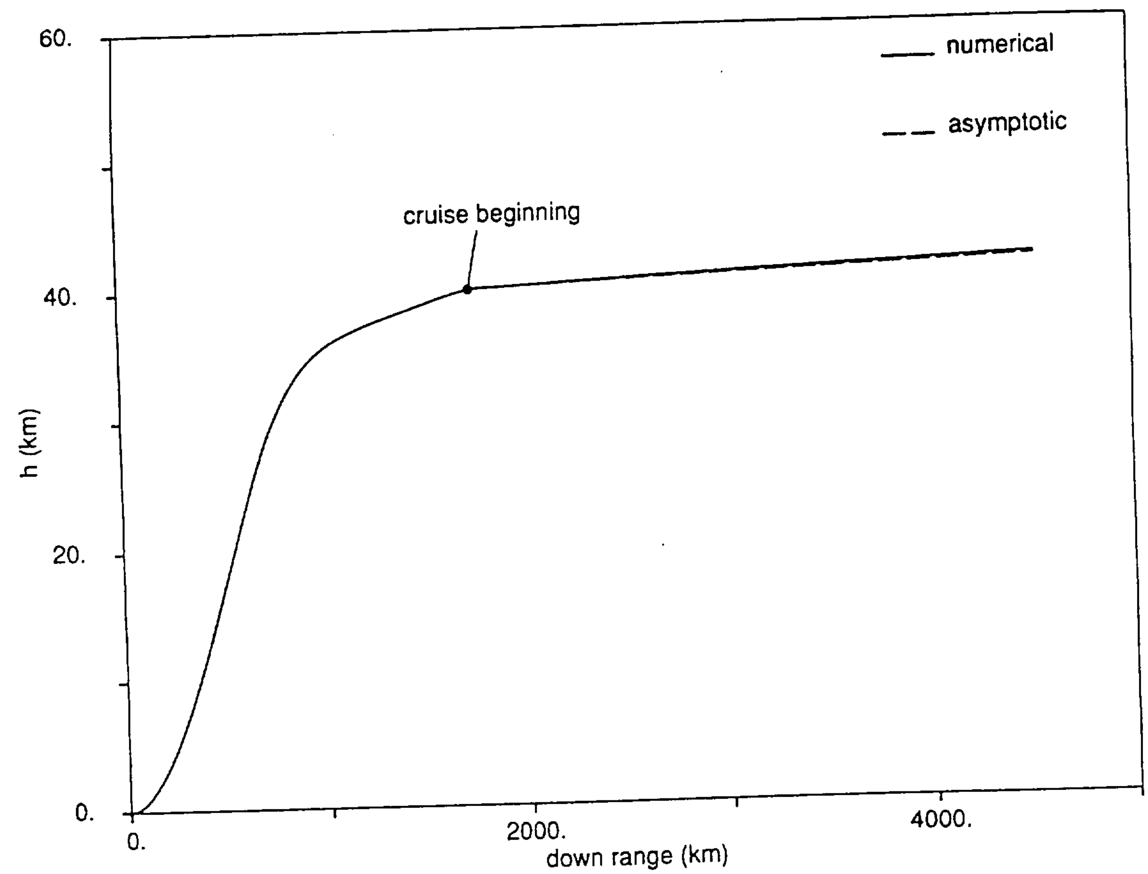

Figure 2. Comparison of numerical and analytical cruise trajectories

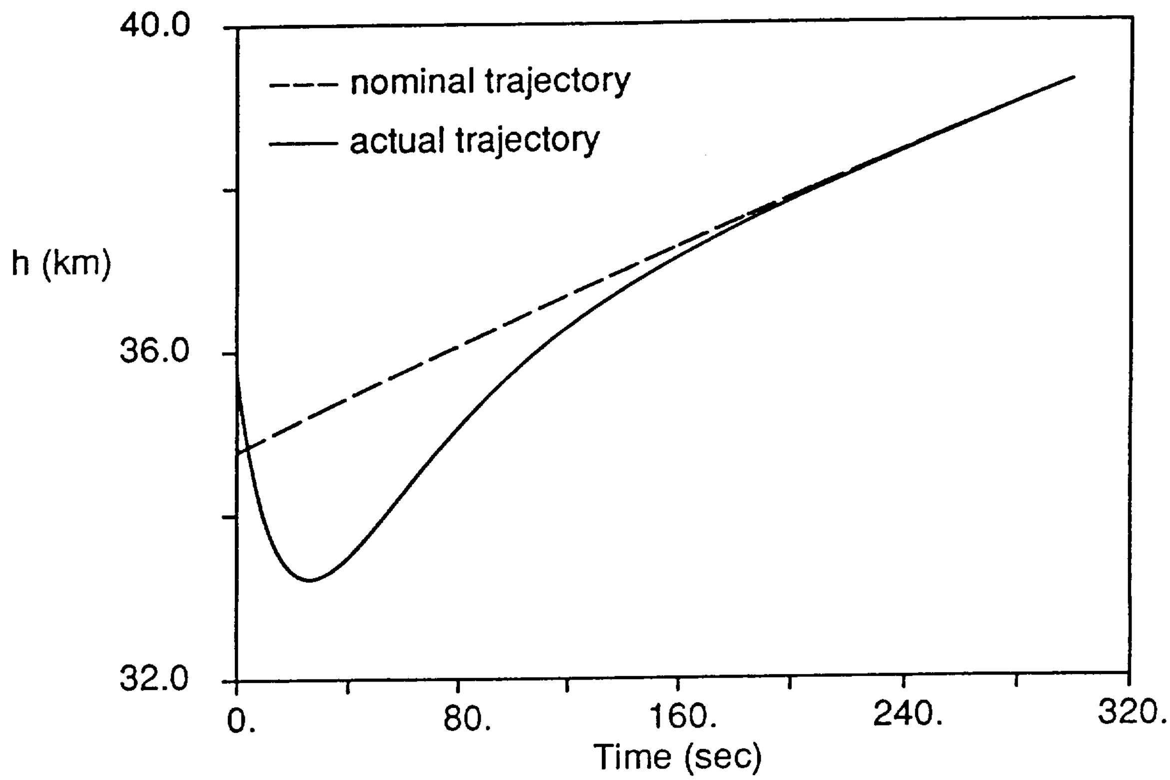

Figure 3. Altitude history with guidance laws based on inverse dynamics

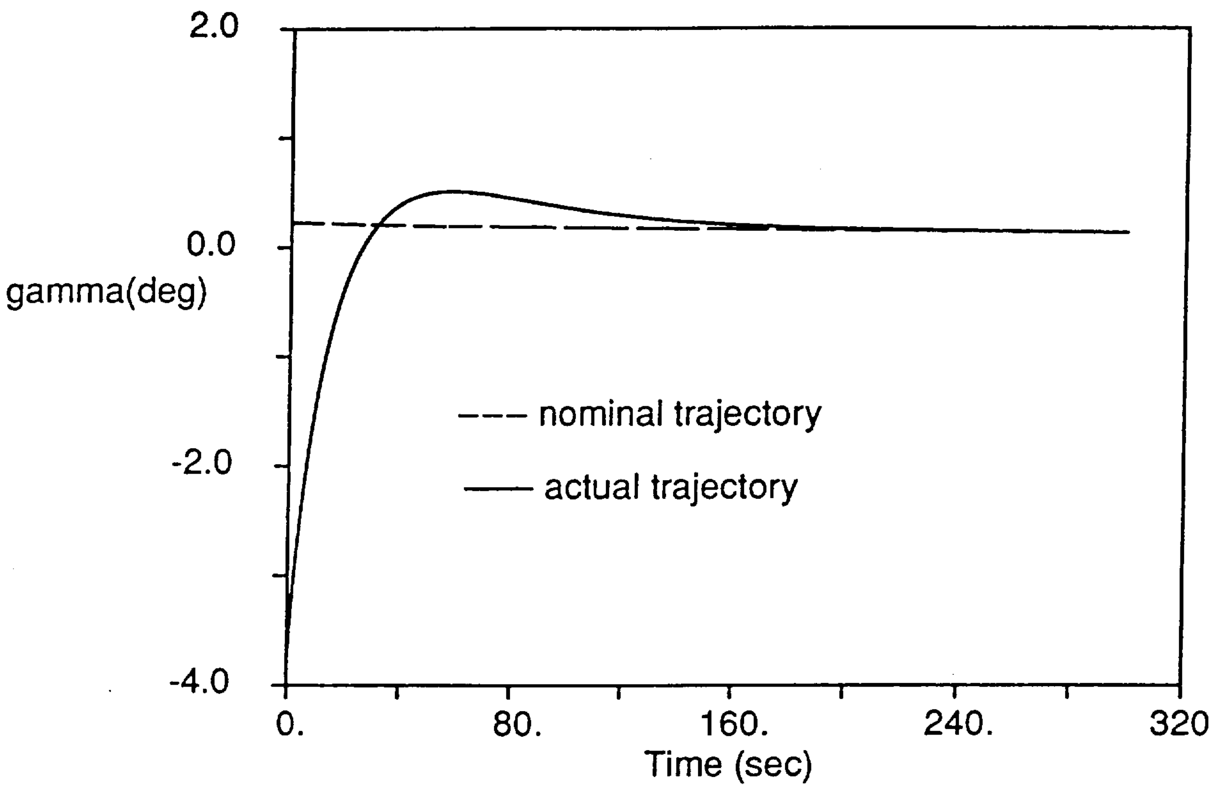

Figure 4. Flight path angle history with guidance laws based on inverse dynamics