V. S. Sohoni

Real-Time Orbiter Abort Guidance

Abstract: This paper describes a real-time abort guidance algorithm which determines the time sequence of the powered maneuvers and the orientation of the thrust vector throughout an abort-mission action initiated during the orbiter ascent phase. It involves guiding a heavily loaded Space Shuttle vehicle, passing through severe environmental conditions, back to a designated landing area. A graphical example and estimates of the computer requirements are included.

Introduction

The function of a real-time guidance scheme for an orbiting space vehicle, or orbiter, is to compute guidance commands that define a trajectory profile from a given (existing) orbiter state to a state determined by certain desired end conditions. Since the orbiter state, especially in the abort mode, is continually perturbed by effects that cannot be incorporated in the guidance model, any real-time guidance scheme requires the ability to take into account all such variations and still produce a satisfactory trajectory profile.

An "abort" is defined as the premature or abnormal termination of a mission as a result of either a system or a human failure which, however, does not incapacitate the vehicle or its control system. For example, suppose that after launching the Shuttle it is discovered that a support system or a docking port on the in-orbit space laboratory has malfunctioned, or that an astronaut has suddenly become ill. In contrast with previous space vehicles that have been recovered, post-mission, by a pre-planned ballistic-trajectory ocean drop, the Space Shuttle is a winged, guidable, and reusable vehicle. Thus, there is good reason to consider the possible aborting of a mission without assuming an intrinsic malfunction of the Shuttle itself, and there is considerable potential and motivation for the undamaged recovery of the vehicle in such a case.

Among all the flight phases of the Space Shuttle vehicle, abort guidance during the ascent phase is the most critical because it involves guiding a heavily loaded vehicle that is passing through severe environmental conditions [1]. This paper describes a predictive guidance algorithm for the the Space Shuttle, which is intended to return the orbiter to the launch site when its nominal mission is aborted during the ascent phase.

The predictive guidance algorithm uses knowledge of the current orbiter state and the desired terminal state, in relation to the landing site, and determines the time sequence of the powered maneuver and the orientation of the thrust vector throughout the abort mode. For example, the magnitude of the down-range component of acceleration, the time at which to begin to return toward the desired landing site, and the radial acceleration necessary to attain the desired terminal altitude (while remaining in the low dynamic-pressure environment) are computed. The key formulations in the predictive guidance algorithm are the analytical expressions for the terminal state that the vehicle will reach for a given sequence of thrust orientations, along with the associated Jacobian matrix; the set of equations and associated definition of symbols may be obtained from the author.

In the terminal phase of the abort mode, the predictive guidance reduces to a velocity-to-be-attained scheme. This has the desirable effect of reducing those deviations in the end-state prediction which result from variations and uncertainties in the vehicle characteristics. Graphical results for a representative abort case and estimates of the computer requirements are also included in this paper.

Problem statement

Contrary to the concept [2] of minimizing fuel consumption during a nominal ascent flight phase, the Space Shuttle orbiter in abort mode is required to deplete its fuel tanks and be separated from the rest of the ascent vehicle. The guidance objective during abort mode is to attain a terminal energy state that is in proper relation to the landing site and is consistent with the aerodynamic heating and loading constraints. In the absence of a well-defined payoff function for optimization during this mode, the abort guidance algorithm presented in this paper is formulated to minimize aerodynamic forces. Minimization of aerodynamic forces is considered important because the abort mode may have weakened the orbiter structure. Immediately after abort mode initia-

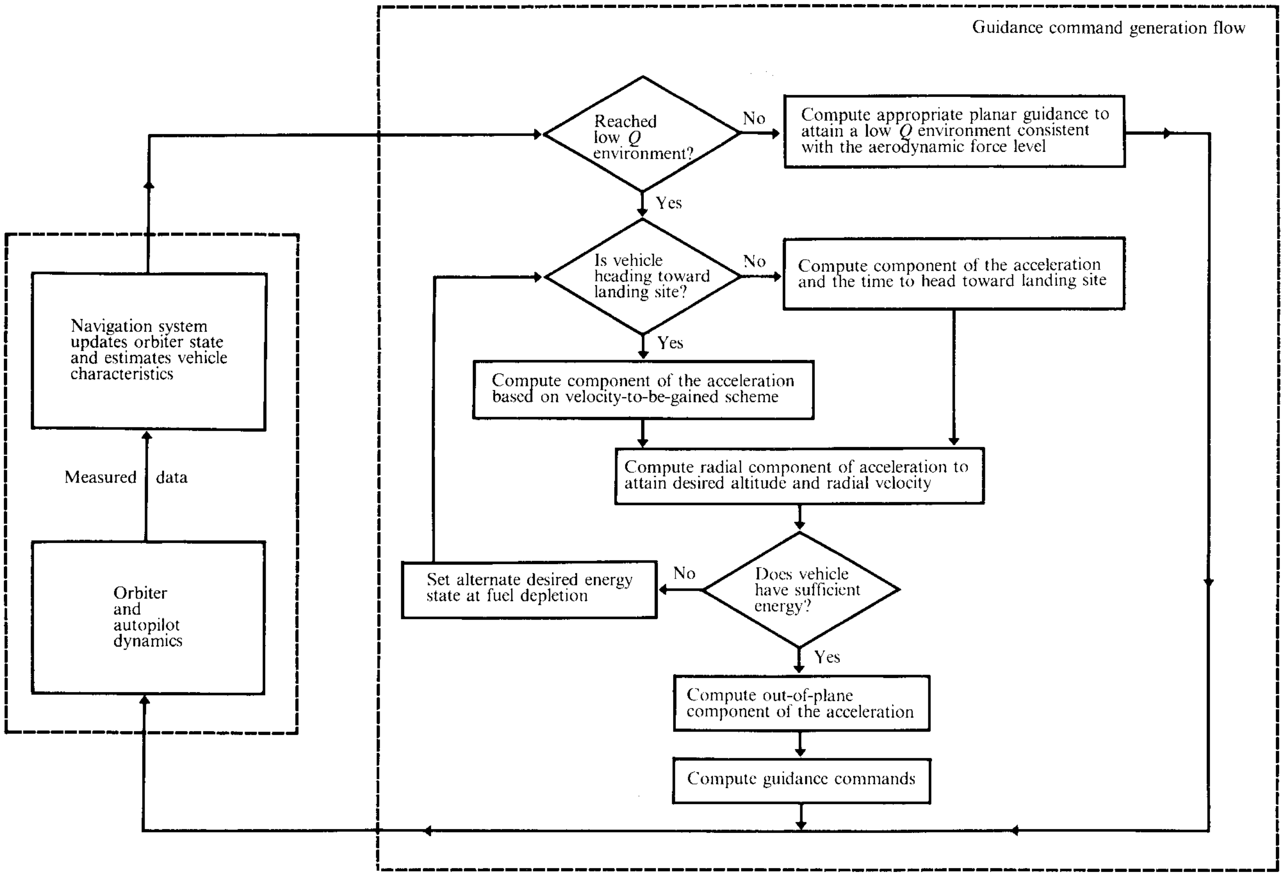

Figure 1 Functional flow diagram.

tion, consistent with the philosophy of minimizing aerodynamic forces, the orbiter is forced to fly a lifting trajectory to attain higher altitude, thereby reaching a low dynamic-pressure environment.

The baseline mission [3] for the Space Shuttle requires that the Shuttle vehicle attain a 50-nmi × 100-nmi (perigee, apogee in nautical miles; 93-km × 185-km) orbit after liftoff. As the result of a system or a human failure the mission may be aborted during the nominal ascent flight, i.e., the flight between liftoff and orbital insertion. As far as abort guidance is concerned, the nominal ascent flight can be divided into three separate segments. The specific guidance policy to be employed depends upon the segment during which the abort initiation occurs.

For the first few seconds after liftoff, the vehicle is in a low dynamic-pressure environment and the solid-fuel-rocket abort motors provide enough energy for the orbiter to glide and land as an aircraft at the launch site. No specific abort guidance command needs to be generated during this first segment of the flight. When the mission is aborted in a high dynamic-pressure environment during the second segment of the ascent flight, the orbiter with its fuel tanks is separated from the rest of the vehicle. The orbiter is then required to deplete the fuel in its tanks and, in the process, to attain an appropriate energy state in relation to the launch site, so that again it can land as an aircraft. The guidance during this phase is critical because of the severe environmental conditions, and the scheme outlined in this paper is specifically designed for this case. When the Shuttle vehicle attains high velocity and high altitude, the dynamic pressure again decreases. If the abort is initiated in this third segment of the ascent flight, the orbiter will have attained enough energy for a "once-around-abort." The guidance policy for a once-around-abort [4, 5] is straightforward and, therefore, is not discussed in this paper.

The specific objective of the real-time guidance scheme addressed in this paper is to generate commands that will take the orbiter from its state at the initiation of the abort mode, during the high dynamic-pressure phase, to a final state from which an unpowered landing can be made at the launch site. At the same time, the command sequence must require enough fuel consumption during the powered portion of the abort to completely deplete

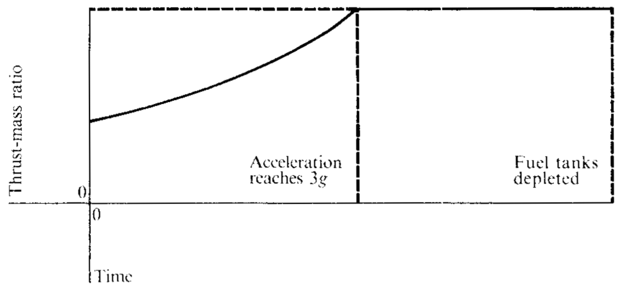

Figure 2 Acceleration profile.

the orbiter's fuel tanks. For example, a relative velocity of approximately 2500 ft/s (762 m/s), oriented toward the launch site, and an altitude of approximately 150000 ft (45.7 km) at a distance of 25 miles (463 km) from the launch site, with negligibly small flight path angle, can be assumed to constitute an appropriate final state for the abort sequence.

Guidance concept

As indicated previously, minimization of aerodynamic forces [6] is assumed to be the payoff function during the abort phase; this results in uniform forces throughout the flight. Instead of solving a boundary value problem for the level of uniform forces, a nominal peak aerodynamic force value is assumed. The basic idea underlying the guidance scheme is to require the orbiter to fly a lifting trajectory to attain higher altitude (a lower dynamic-pressure environment) as soon as possible (while minimizing aerodynamic forces). At higher altitudes the vehicle can perform large yaw maneuvers without developing significant aerodynamic forces. At these altitudes, the orientation of the thrust vector is maintained such that at fuel depletion, the vehicle will have attained the desired energy state in relation to the landing site. The return-to-launch-site abort guidance concept is implemented under the following assumptions:

- There is instantaneous separation of the orbiter and its fuel tanks from the rest of the Shuttle vehicle.
- All orbiter systems are operational in their normal sense.
- The acceleration will not exceed $3g$ throughout the powered flight.
- The vehicle can stand up to a specific level of normal force.
- The orbiter wings will remain at right angles to the local vertical throughout the powered flight.

The functional flow of the command sequence is shown in Fig. 1.

During the ascent, the Shuttle vehicle is required to follow a planar steering course. From the time of abort initiation until the vehicle reaches a specific low dynamic-pressure environment, the planar steering is continued except that a specific aerodynamic normal force is maintained as shown in Fig. 1. This guidance policy allows the Shuttle vehicle to attain a low-pressure environment as early as possible.

From the time the Shuttle vehicle reaches the low-pressure environment until the depletion of the fuel in the tanks, as shown in Fig. 1, the guidance commands are computed as described in the following steps.

1. Compute the remaining burn time consistent with the g-loading constraint and the time at which the contraint becomes active (see Fig. 2).
2. Determine a local vertical plane that passes through both the vehicle's current position and the landing site.
3. Determine the vehicle's radial velocity and altitude, the velocity component perpendicular to the radius vector that lies in the plane determined in step 2 and the current down-range travel.
4. Since the vehicle mass is a monotonically decreasing function of time, the vehicle acceleration continuously increases until the g-constraint becomes active. Therefore, the acceleration profile (see Fig. 2) of the vehicle is a known function of time. Given the down-range travel, the velocity, and the total burn time, compute the value of the acceleration that is consistent with the acceleration profile and the amount of time required to burn in the down-range and up-range directions such that the vehicle will be at the desired down-range distance with appropriate velocity at mission termination.
5. Make a similar calculation using the radial velocity and the current altitude.
6. If the root-mean-square value of the accelerations found in steps 4 and 5 is smaller than the current vehicle acceleration, then the difference acceleration is to be oriented perpendicular to the plane determined in step 2.
7. At every guidance cycle, the orientation of the thrust is determined through steps 4, 5, and 6 until the vehicle turns around; then a velocity-to-be-gained scheme is used.
8. If the vehicle has insufficient energy to attain the desired state at mission termination, this information is available at the initiation of the maneuver so that an alternate final state can be chosen.

Example

A nominal ascent mission of a 50-nmi × 100-nmi (93-km × 185-km), 50° inclined orbit for the Shuttle vehicle configuration was considered for the test case. The details of the mission are as follows:

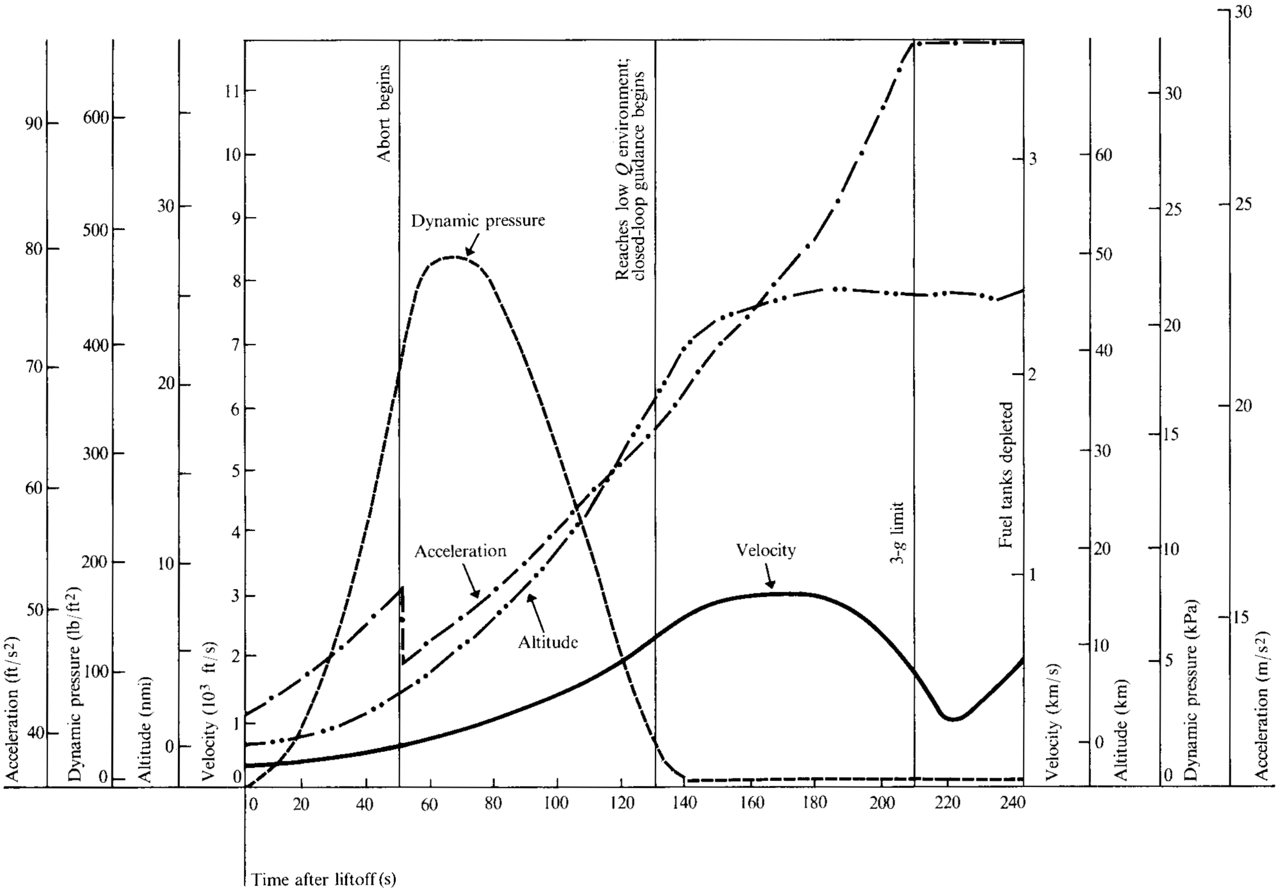

Figure 3 Ascent profile for abort mode initiated 50 s after liftoff.

Launch site	– Kennedy Space Center
Launch azimuth	– 36.8° north
Launch mass	– 5 047 327 lb (2 289 429 kg)
Orbiter mass	– 859 234 lb (389 742 kg)
Booster mass	– 4 188 093 lb (1 899 687 kg)
Thrust-mass ratio at liftoff	– 1.31
Nominal separation time	– 214 s after liftoff
Nominal insertion time	– 407 s after liftoff

Mission abort is assumed to take place 50 s after liftoff. Instantaneous separation of the orbiter from the booster is assumed to occur at this time and the abort guidance is initiated for the orbiter to return to Kennedy Space Center. After initiation of the abort mode, the orbiter is required to attain a low dynamic-pressure environment as early as possible, without exceeding a normal force of 300000 lb (1.36×10^5 kgf), at which time the closed-loop guidance is initiated. During the closed-loop guidance, the orientation of the orbiter thrust vector is maintained such that at fuel depletion, the orbiter attains the following state:

Relative velocity	– 2 500 ft/s (762 m/s) oriented toward Kennedy Space Center
Altitude	– 150 000 ft (45.7 km)
Flight path angle	– 0
Distance from Kennedy Space Center	– 25 mi (46.3 km)

Figure 3 shows (a) the nominal ascent profile for the composite vehicle for 50 s after liftoff, (b) the abort profile for the orbiter vehicle to attain a low dynamic-pressure environment [$\leq$ 35 lb/ft^2 (1.68 kPa)], and (c) the closed-loop guidance phase. The orbiter vehicle reaches a low dynamic-pressure environment after 130 s in flight, at which time the closed-loop guidance is initiated. A 3-g constraint becomes active at 210 s in flight. The abort guidance is terminated at fuel depletion, i.e., at 245 s after liftoff.

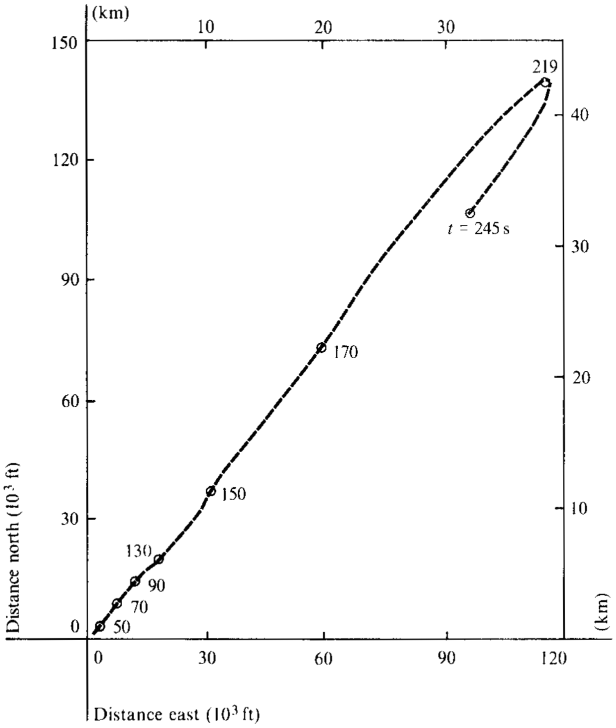

Figure 4 Ground track of vehicle after liftoff.

Figure 4 shows the ground track of the vehicle from liftoff through 245 s. At that time the orbiter is heading toward the Kennedy Space Center and is approximately 25 miles away when the abort guidance phase is terminated.

The storage requirement for the guidance algorithm is estimated to be approximately 2 000 32-bit words if used in its current form. Even though the guidance sequence has been described only for the case in which the vehicle returns to the launch site, it can be easily implemented such that the vehicle may land at any alternate site. Because of the fast execution time for each guidance cycle and relatively small computer storage requirement, this guidance scheme appears to be a feasible real-time guidance algorithm during the abort mode.

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The author is located at the IBM Federal Systems Division, 150 Sparkman Drive NW, Huntsville Alabama 35805.