Guidance of Terminal Area Energy Management Trajectories for Re-entry Vehicles

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***Abstract*: *One of the most critical periods of a space-plane re-entry is the Terminal Area Energy Management (TAEM) phase, where performance utilizing on-board generation is required. The ability of an autonomous Reusable Launch Vehicle (RLV) to recover from unforeseen disruptions is considerably enhanced by on-board trajectory-generating capabilities. Contemporary guiding approaches can reduce operational expenses and design time by utilizing modern computer power and faster algorithms. Also, it is increase the RLV mission resilience and efficiency at the same time. In this paper, the complete method of how to control and land an RLV, using the guidance system and control algorithms during the TAEM phase of re-entry has been discussed. The paper has been produced after thorough research on the newer guidance techniques, control laws and the guidance algorithms which relate mainly to the TAEM phase.*

Key Words: *TAEM phase, Trajectory algorithm, Guidance system, Auto Landing*

1. INTRODUCTION

The initial re-entry (IRE) phase of an RLV atmospheric re-entry is frequently followed by a terminal area energy management (TAEM) phase, and finally an approach and landing phase (A&L). The Terminal Area Energy Management (TAEM) phase of re-entry begins at 30 kilometres altitude with a Mach number of 2.5 and finishes at 2 kilometres altitude with a speed of 125 kilometres per second. The primary purpose of the TAEM phase is to dissipate the vehicle high potential energy during the re-entry to a certain end condition while staying within the design parameters. After the TAEM phase, the vehicle must be aligned with the runway for the ALI (Auto Landing Initiation) phase.

Most of the re-entry guiding technique focuses primarily on the high-Mach atmospheric entry phase, where thermal heating considerations are critical. On-board trajectory creation capabilities have been the subject of a few research publications focusing on lower Mach flying regimes.

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Since ancient times, entry procedures and guidance systems have undergone extensive evolution.

The engineers were limited by the processing power and memory available at the time. These limits have been effectively reduced due to new guidance methods for RLVs that employ the Shuttle Guidance and Control framework.

To take full advantage of aerodynamic flight maneuvers in runway targeting in the ALI phase, these guidance systems rely on mission planners, trajectory generators, and other algorithms.

It appears that no guidance system has been devised that can handle all abort circumstances.

2. TRAJECTORY ALGORITHM

2.1 Equation of Motion

The equations of motion for a vehicle in atmospheric flight are used extensively in the trajectory creation approach.

All nonlinearities, including three-dimensional wind effects, have been retained for accuracy. However, the derivations for these algorithms include certain important design assumptions that help to simplify the formulation.

These assumptions are outlined in the table below.

- No propulsion is produced by the vehicle.
- The trajectory generator will always create turns that are well-coordinated.
- The vehicle will always be in a static trim position.
- all side forces (Y) are negligible
- The winds are consistent, despite variations in height or position.
- The Earth is flat, non-rotating, and is approximately inertial [2]

$$F\ = x\hat{\imath}, + y\hat{\jmath}_i + \ z\widehat{k_\imath} \tag{1}$$

$$\vec{V_\imath} = \frac{d\vec{r}}{dt} = \dot{x}\hat{\imath}_h + \ \dot{y}\hat{\jmath}_h\ - \dot{h}\widehat{k_h} \tag{2}$$

$$\overrightarrow{a_a} = \dot{V}_a\widehat{\imath_a} + V_a\dot{\varphi_w}\cos\varphi_w\,\widehat{\jmath_a} - \ V_a\dot{\varphi_w}\widehat{k_a} \tag{3}$$

The Lift and Drag forces can be written as functions of the dynamic pressure q, the vehicle planform area S, and the dimensionless coefficients of Lift and Drag, CD and CL, in any of the previous equations.

$$L = \bar{q}SC_L \tag{4}$$

$$D = \bar{q}SC_D \tag{5}$$

2.2 Overview

The aim of the guidance control is to guide the spacecraft to a runway for landing without disturbing any constraints.

There are many constraints such as limiting aero thermodynamic heating levels, dynamic pressure and the loading due to acceleration. The old guidance and control system developed for the shuttle consisted of two parts, the guidance algorithm that controls the vehicle's trajectory and energy and the flight control algorithm that translates the guidance inputs into the vehicle response [1].

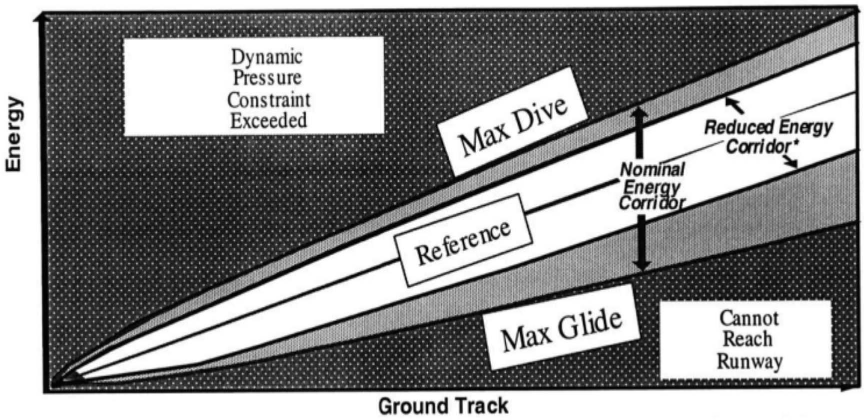

Fig. 1 – An example of a shuttle energy corridor [2]

A pilot acts as an intermediary between these two systems but using the similar structure of guidance and control for future flights of unmanned Reusable Launch Vehicle (RLV) will pose limitations as there is no human intelligence presence to compensate for the errors in the autonomous G&C methodology [2].

2.3 Energy Corridors

Energy corridors are the tools that are used to predict a vehicle's ability to meet range requirements while in the satisfactory energy constraint range. During the TAEM phase, the guidance system takes into consideration the total energy in the weight-energy equation and attempts to keep the space shuttle in the centre of the energy corridor. The corridor is divided into 3 distinct parts i.e., Max dive, Max Glide and Reference. The Max dive line represents the elevated descent path that a space shuttle follows without having to face any dynamic pressure disturbances. At a given energy level, the max dive will generate the shortest distance to the ground.

The Max glide line represents the energy decay of a space shuttle flying at a maximum lift through the drag ratio. If a space shuttle goes below this max glide path, then it will not reach the runway.

$$\frac{E}{w} = h + \frac{\bar{q}}{\rho q} \tag{6}$$

The reference line is the path that is decided by the mission planners for the space shuttle to undergo a nominal E/W value. This line depicts to the nominal altitude and dynamic pressure profiles and provides the basis for a safe flight [2].

2.4 Dynamic Pressure Schedule/profile

After the completion of TAEM subphase, there needs to be trajectory designed to reach the vehicle to the approach and landing. The target conditions at Auto landing Interface are reached by the dynamic pressure schedule. There are two parts governing the dynamic pressure profile and those are: Dynamic constraints and Geometric constraints.

The dynamic requirements at ALI are defined by the dynamic pressure transitions. The trajectory is defined by the use of dynamic pressure. The geometric constraints which are important to ALI are the downrange, cross range and altitude position with respect to the runway.

To make the trajectory for the vehicle to reach ALI, the dynamic pressure scheduling is the method to be used. A constant q profile or a changing pressure path is chosen for the trajectory development. One approach is to use the differential of dynamic pressure $\frac{d\bar{q}}{dh}$ to make sure that the vehicle reaches the final point from the initial point without any discontinuities or dynamic violations.

2.5 Limitations of TAEM Guidance

Because of the inefficiency of the lengthy mission planning phase, was not much progress in the TAEM phase. To begin with, the acquisition phase uses constant bank angles and produces a circular segment for small degrees of rotation, but for greater angles of rotation, the space plane spirals due to the decrease in velocity and increase in density [3], [4].

The HAC (Heading Angle Cone) is positioned at a predetermined distance from the runway. Even though transferring the HAC is a possibility, it can only be done once from NEP to MEP. Because of this insufficiency, fine-tuning the lateral trajectory is difficult and there is a chance that it will force the vehicle to go from a low E/W state to a high E/W state, generating instability. To surpass all these limitations, a new guidance approach needs to be generated that gives a faster and a robust approach to design the offline trajectories developing an on-board trajectory control.

3. RESEARCH ON THE EXISTING ALGORITHMS

3.1 New Methodologies for On-board Generation of TAEM Trajectories for Autonomous RLVS

3.1.1 Overview

A guidance system for the TAEM phase is being put forward in this paper. For this, a mathematical model of the gliding motion of a reusable launch vehicle is made with the equations governing the dynamics for the reference profile generation. The reference longitudinal profile can be obtained from the max dive and max glide that the RLV can undergo. The trajectory is obtained by using the equations of motion and iterating it at each altitude [5].

3.1.2 Mathematical Model

A three-dimensional glider motion is developed for the RLV, and the required equations of motions are deduced under TAEM phase, where V is velocity, gamma is the flight path angle, Ψ is the heading angle, h is the altitude, μ is the bank angle, m is the mass and g are the gravitational force of attraction. The dynamic pressure equations are also developed as follows:

$$\bar{q} = 0.5\,\rho V^2 \tag{7}$$

$$\frac{dV}{dt} = -\frac{D}{M} - g\sin\gamma \tag{8}$$

$$\frac{d\gamma}{dt} = \frac{L\cos\mu}{mV} - \frac{g}{V}\cos\gamma \tag{9}$$

$$\frac{d\varphi}{dt} = \frac{L\sin\mu}{mV\cos\gamma} \tag{10}$$

$$\frac{dx}{dt} = V\cos\gamma\cos\varphi \tag{11}$$

$$\frac{dy}{dt} = V\cos\gamma\sin\varphi \tag{12}$$

$$\frac{dh}{dt} = V\sin\gamma \tag{13}$$

These equations are known as KEP equations.

These are the equations which are required to generate the reference trajectory. The KEP equations are basically re-arrangements of dynamic pressure profile and altitude. By taking the differential of dynamic pressure we get: - [6], [7]

$$\frac{d\bar{q}}{dt} = \frac{\rho}{\sin\gamma}\frac{dh}{dt}\frac{dV}{dt} + \frac{d\rho}{dt}\frac{\bar{q}}{\rho} \tag{14}$$

Differentiating the dynamic pressure w.r.t the altitude, we get: -

$$\frac{d\bar{q}}{dh} = \frac{\rho}{\sin\gamma}\frac{dV}{dt} + \frac{d\rho}{dh}\frac{\bar{q}}{\rho} \tag{15}$$

The differential of ground track range R w.r.t time is: -

$$\frac{dR}{dt} = V\cos\gamma \tag{16}$$

Differentiating ground track range R with altitude h is: -

$$\frac{dR}{dh} = \frac{1}{\tan\gamma} \tag{17}$$

3.1.3 Development of Guidance System

Two conditions must be met while creating the guiding system. These are: -

1. The design restrictions of the space shuttle, namely the load factor and dynamic pressure.
2. The ALI end requirements that must be satisfied (ALI). The limits on dynamic pressure, flight path, and heading angle are as follows.

ALI is located at xALI =yALI = 0 feet and has an altitude of hALI = 110,000 feet. The optimal dynamic pressure for ALI is qALI = 255psf at (VALI =539ft/s; M =0:5). is the ideal dynamic pressure for ALI. Altitude, velocity, heading angle, and bank angle are all part of the trajectory instructions [8], [9].

3.1.4 Longitudinal Trajectory Generation

The aim is to create dynamic pressure as a function of altitude and use an iterative algorithm to calculate the corresponding states history. Prior to trajectory development, a dynamic pressure profile representing the longitudinal properties of a RLV is defined. To reach its maximum range, an RLV can fly at its maximum L/D ratio [10].

However, if the RLV continues on this course, system states like alpha, gamma, and q will experience chattering. As a result, a constant dynamic pressure profile is avoided. Figure 2 represents the TAEM guidance system's schematic diagram. Figure 3 shows how the trajectory iteration scheme works and it is a closed loop scheme which aims to reduce the error to zero.

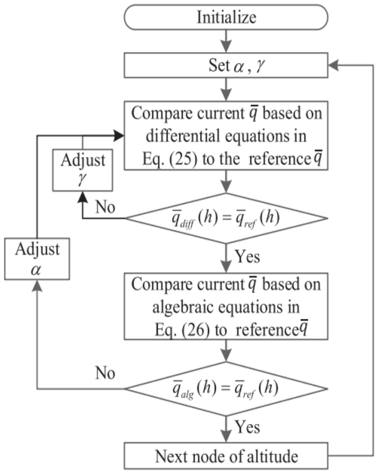

Fig. 2 – Iteration method for the TAEM trajectory [3]

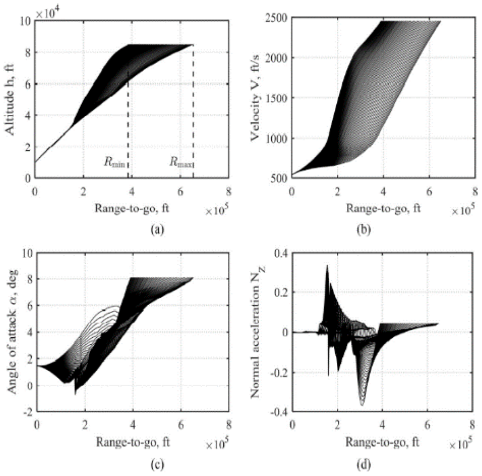

Fig. 3 – For varying dynamic pressures, the state histories versus range-to-go [3]

3.1.5 On Board Ground Track Predictor

The ground-track path is made up of three main sections. It begins with TEP and continues with the acquisition phase (AC), in which the RLV turns to align its heading with a tangency point on the HAC. The onboard ground track predictor is then built to give two key properties based on the established ground-track path.

1) At the terminal entry point, the vehicle's entire range-to-go is estimated, which is utilised as an index to determine the best path to take [11], [12].

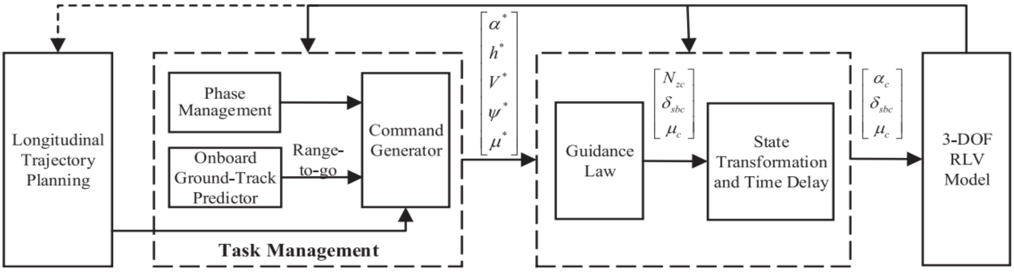

Fig. 4 – Schematic diagram generated for the trajectory generation under the TAEM phase

2) During the TAEM flight, the range-to-go at each point on the flight path is predicted in real-time, and reference commands are generated, based on this information.

This figure shows the ground track phases that a space shuttle goes through, while reaching the runway.

3.1.6 Simulation

The longitudinal profile is generated from a TEP altitude of 85000 ft with the dynamic pressure of 200 psf. The terminal altitude and terminal dynamic pressure are set as h=10000ft and q= 255 psf [13].

Table 1 – Control gains at each altitude points [3]

Height, 10^4 ft	1	2	3	4	5	6	7	8	8.5
K_H, 10^{-3}	3.0	2.4	1.4	1.2	0.9	0.7	0.6	0.5	0.4

K_{HI}, 10^{-4}	3.0	2.6	2.4	2.0	1.0	1.0	1.0	1.0	1.0
K_{HD}, 10^{-3}	1.5	1.5	1.3	1.3	0.9	0.8	0.7	0.6	0.5

The control gains are deduced at each altitude point and those are tabulated in Table 1. For different dynamic pressure, the state systems w.r.t the range to go changes and those changes are depicted in figure 4.

4. RESULTS

Guidance Scheme for Horizontal Motion

The horizontal motion is depended on the ground track geometry. The dashed line represents the distance from the start of TEP i.e. z_0 to x_d.The vertical guidance determines the downrange, and the groundtrack should have the same length as the downrange. The initial groundtrack is shorter than the downrange, so the RLV takes a detour. The ground track is a combination of circles and straight lines.

The vehicle flies a right turn around m1, following a tangential line to m2, where the vehicle takes another right turn to m2 followed by the tangent to m3 and a left turn at m3 to reach the runway which is showed in Figure 5. The total length of the ground track from the above figure is:

$$s = arc_1 + len_1 + arc_2 + len_2 + arc_3 \tag{18}$$

A controller is designed for the horizontal guidance, the same way it was designed for vertical guidance. For the horizontal guidance, the controller needs to cover two situations flight along a straight line and fight along a circle explained in Fig. 5.

The state variables that are required for the guidance are *r*, Ψ. The design differential equations are: [14], [15]

$$\dot{r} = V_h \sin\psi \tag{19}$$

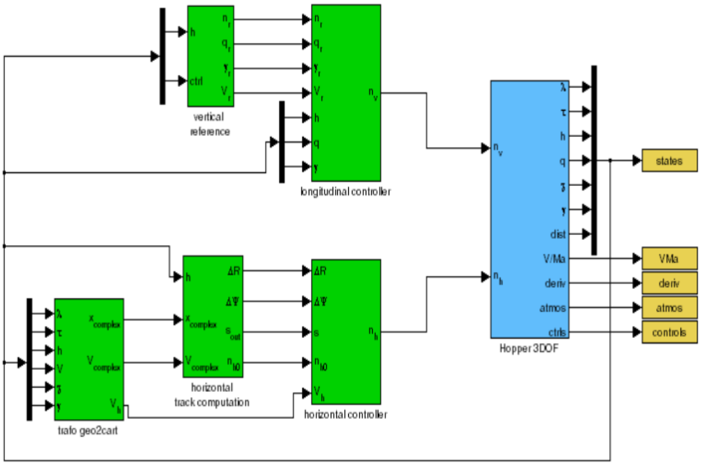

Fig. 5 – Horizontal Guidance Design

Here, if s=1 will lead to a right turn and s= -1 will lead to a left turn. Here the control is the horizontal load factor n_h and the trim value for constant turn is kept as 0.

The control law is: -

$$\Delta n_h = -k_1 \Delta r - k_2 \Delta \psi \tag{20}$$

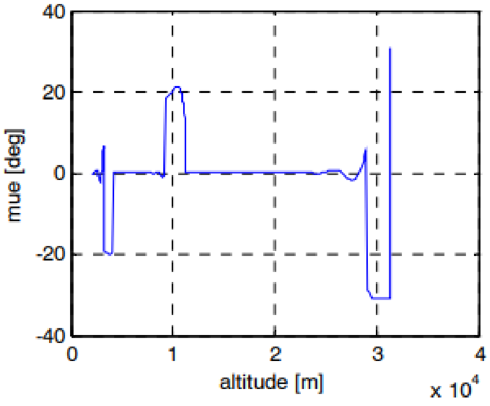

Fig. 6 – Bank angle vs. Altitude

The gains k_1 and k_2 are: -

$$k_1 = \frac{\sigma^2}{g\zeta} s$$

$$k_2 = \frac{2\sigma}{g} V_h$$

The control law mentioned above can be used for straight line where n_{hr}= 0 and $\Delta\psi$ = 0. This is the guidance loop that is used in this paper. Here, the states outputs are the angle of attack [16], [17]

Simulation

This paper also proposed the calculation for downrange caused by the different bank angles Figure 4 shows that the range correction due to change in the bank angle. If a same bank angle is used, then it will increase the drag, which will decrease the path inclination angle.

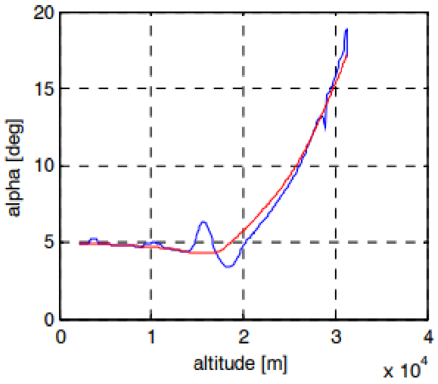

Fig. 7 – Angle of attack vs Altitude

The above figures depict the graphs between the bank angle vs altitude and angle of attack vs altitude, which is explained in Figure 6 and Figure 7.

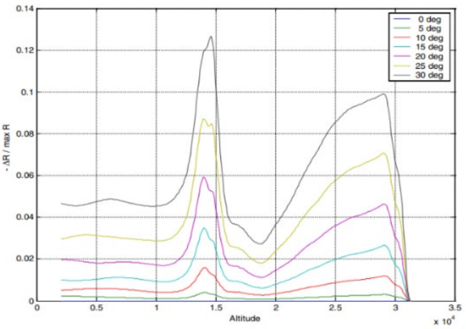

Fig. 8 – Range Correction for Downrange

5. CONCLUSIONS

As we see from the literature review and from the dataset provided, the guidance algorithm for the TAEM phase has gone through a lot of developments since the early days when it was first developed. Modern researchers make extensive use of the available computing power and memory storage to arrive at a guidance algorithm that has very few errors. The guidance algorithm is still under research, and researchers have been able to present guidance algorithms based on various techniques like predictor-corrector, which is an optimization technique.

As the rate of data transfer has improved, researchers are focusing more on the online trajectory generation rather than the offline counterpart. A self-adapting guidance system has also come into the picture where the control system adapts itself to the external disturbance in the environment. The guidance has come a long way from where it started, and it will continue to be developed in the future.

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