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Pattern Search Optimization Applied to Spacecraft Re-entry Trajectory

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Abstract—*Objective of the study is to optimize the spacecraft re-entry trajectory using Pattern Search (PS) technique. Aerodynamic performance (L/D) is used as a control parameter for trajectory shaping to keep the vehicle generic. Optimized L/D profile is achieved such that, minimizing the objective function (with and without integrated heat load term) subject to terminal conditions and path constraints. Comparison of with and without integrated heat load terms are presented. Results agree with the expected trends.*

Keywords: *Re-entry, Trajectory, Optimization, Pattern Search, Aerodynamic performance.*

NOMENCLATURE

L	Lift
D	Drag
V	Velocity
γ	Flight path angle
h	Altitude
r	Range
Re	Earth radius
g	Acceleration due to gravity
ρ	Atmospheric density
h_f	Heat flux
L_f	Deceleration load factor
C	Constant
q_∞	Dynamic pressure
B	Ballistic coefficient
m	Mass of the vehicle
C_D	Drag coefficient
S	Surface area

1. INTRODUCTION

Reusable space vehicles are the promising candidates for the future low cost transportation systems. Descend of the space vehicle broadly consists of Keplerian, Re-entry and Landing phases.

Huge amount of kinetic and potential energy acquired by the vehicle need to be dissipated during the atmospheric entry. Thermal and deceleration loads need to be within permissible limits during this energy dissipation to ensure vehicle integrity.

Controlled dissipation of energy, uncertainties in atmospheric parameters and coupled dynamics (aero & flight) makes the Re-entry phase most challenging.

An attempt has been made to use the aerodynamic performance as a control parameter for the trajectory optimization [1] under fair assumptions and constraints. The details are discussed in following sections.

2. PROBLEM DEFINITION

2.1 Objective

Objective of the study is to optimize the spacecraft reentry trajectory using pattern search technique, lift to drag (L/D) ratio as a control parameter.

2.2 Reentry Vehicle Dynamics Equations

Fig. 1 shows sign convention.

The ordinary differential equations defining the reentry vehicle trajectory are derived from the lift and drag forces acting on the vehicle with respect to the body frame, absolute velocity with respect to the local frame [2-4].

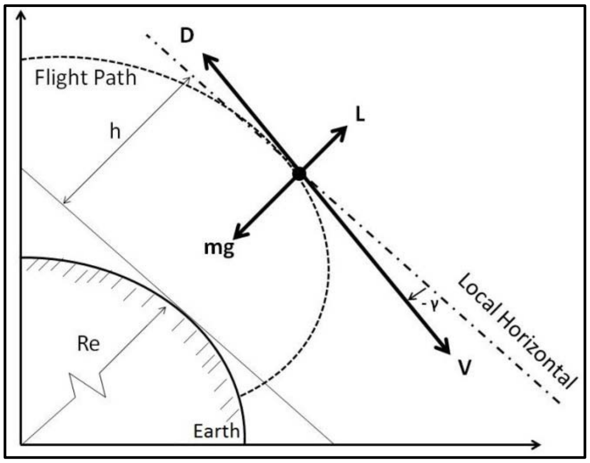

Fig. 1: Sign Convention

$$\dot{V} = -\frac{\rho V^2}{2B} - g\sin\gamma$$

$$\dot{\gamma} = \frac{\rho V (L/D)}{2B} - \frac{g\cos\gamma}{V} + \frac{V\cos\gamma}{Re+h}$$

$$\dot{h} = V\sin\gamma$$

$$\dot{r} = V\cos\gamma$$

Where,

$$g = g_o \left(\frac{Re}{Re+h}\right)^2 ;$$

$$Re = 6378000\ m ;\ g_o = 9.81 \frac{m}{s^2} ;\ B = \frac{m}{S\,C_D}$$

Additional calculations

$$h_f = \frac{C\,V^3\sqrt{\rho}}{\sqrt{R_n}} ;\ L_f = \frac{\dot{V}}{g_o}$$

$$Where,\ C = 1.83 \times 10^{-4}\ \frac{kg^{1/2}}{m}$$

2.3 Assumption

- Vehicle dynamics equations :
1. Point mass model
2. Planar motion
3. Spherical non-rotating earth
- Standard atmospheric model
- Gravity: Earth has a radially symmetric mass distribution.
- Drag coefficient C_D is constant for the vehicle during re-entry

2.4 Constraints

$$h_f \leq h_{f\_limit}$$
$$L_f \leq L_{f\_limit}$$
$$h < h_{max}$$

Constraint on Altitude ‘h’ is to ensure trajectories not to skip out.

3. METHODOLOGY

The above mentioned problem could be treated as a nonlinear constrained optimization. Various methods have been established to address this category. Indirect method use conventional optimization algorithm, especially the algorithms based on gradient, which are very sensitive to initial guess [5-6].

Direct methods does not require gradient of the function. Objective function is reduced at each iteration and to achieve this it may be necessary to modify the calculation of the search direction to ensure that it is downhill. A consequence of this is that the region of convergence for an indirect method may be considerably smaller than the region of convergence for a direct method.

Genetic algorithms (GA) are intelligent global search optimization method based on the natural selection and genetic mechanics. It is robust, not sensitive to initial guess and with good performance to some large-scale nonlinear complex global optimization problems [7-8]. Generally solution depends on fineness of the grid. Finer the grid, higher the time required to generate a solution. However it is observed that, GA takes more computational time for bigger search spaces [9].

Unlike evolutions of generations in GA, PS varies the search space parameter at a time by steps of the same magnitude, and when no such increase or decrease in any one parameter further improved the fitness value, it halved the step size and repeats the process until the steps were deemed sufficiently small. MATLAB R13b inbuilt PS functions have been utilized to solve the problem.

4. TYPICAL REENTRY TRAJECTORY

4.1 Simulation Conditions

Spacecraft Constants[10] : m ; C_D ; S ; R_n

Initial Conditions : [$V_0\ \gamma_0\ h_0\ r_0$]

Terminal Conditions : $[V_f \gamma_f h_f r_f]$

Objective Function :

$$J = K1 * (r_d - r_f)^2 + K2 * (\gamma_d - \gamma_f)^2$$
$$+ K3 * (V_d - V_f)^2$$

Subscripts '*d*' and '*f*' indicates desired and final values of corresponding states respectively. *K1*, *K2* and *K3* are the weights.

$K1 = 1$; $K2 = 3.28280654 \times 10^{11}$; $K3 = 4 \times 10^6$

Weights are calculated based on appropriate acceptable dispersions on the respective terminal states viz., 10 km, 1 deg and 5 m/s.

Problem states the fore mentioned objective function has to be minimized subject to constraints[1] with the following limits

$$h_{f\ limit} = 500 \times 10^4 \frac{W}{m^2}$$
$$L_{f\ limit} = 8\ \mathrm{g}$$
$$h_{max} = 73640\mathrm{m}\ \text{for t} > 100\ sec$$

Search Space : Control input (L/D) within ± 0.5 with the resolution of 0.01 for every 30 sec time step.
Data between the discrete time steps is linearly interpolated.

Initial Conditions :
$[V_0 \gamma_0 h_0 r_0]$ =

[10738 m/s ; -7.14*pi/180 rad ; 121920 m; 0 m]

Terminal Conditions :
$[V_f \gamma_f r_f]$ =

[135 m/s ; - 65*pi/180 rad ; 3881000 m]

Integration time step is 100 milli-seconds and it terminates when vehicle reaches altitude of 10000 m.

4.2 GA Option Settings

No.of Variables : 28

Default settings of PS have been used.

Initial Mesh Size : 1

(Length of the shortest vector from the initial point to a mesh point)

Max.Iterations : 100 * No. Of variables

Max.Fun.Evals : 2000 * No. Of variables

Mesh Contraction: 0.5

Mesh Expansion : 2.0

Initial Penalty : 10

Penalty Factor : 100

TolMesh : 1×10^{-6}

(Minimum tolerance for mesh size)

Convergence Criteria : The algorithm stops if the mesh size becomes smaller than *TolMesh*.

4.3 Results

Fig. 2 shows (semi log plot) indicating convergence of PS over the Iterations. It can be seen from the plot that the magnitude of fitness value decreases as iterations progresses and it is converged.

The best fitness value achieved is 1.129×10^{-4}over 6572 iterations. This resulted in a zero terminal error.

Fig. 3 to Fig. 5 shows various plots describing the characteristics of vehicle dynamics. Fig. 6 shows optimized L/D profile.

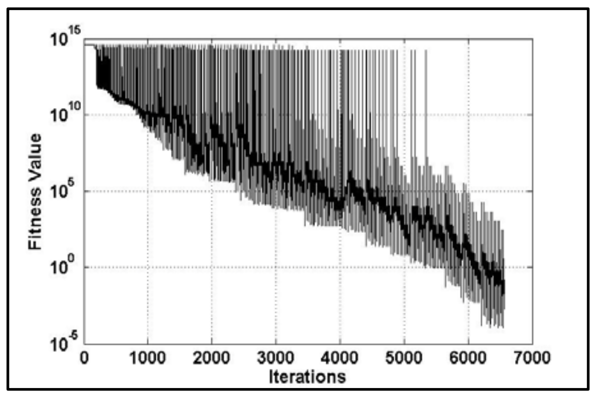

Fig. 2 : Convergence

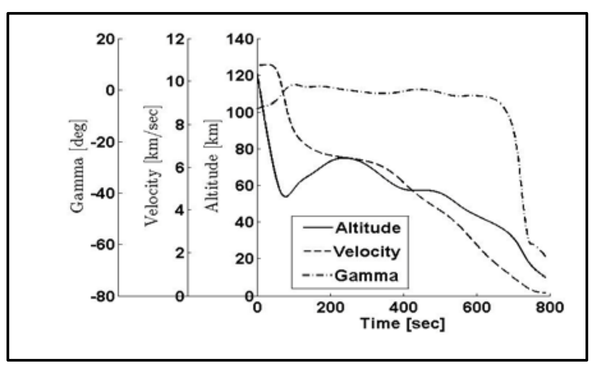

Fig. 3 : Altitude, Velocity and Gamma variation with Time

[1] Integration is terminated subject to constraint limits.

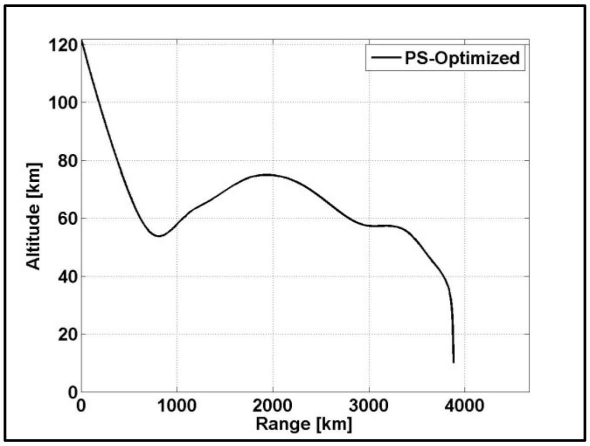

Fig. 4 : Trajectory

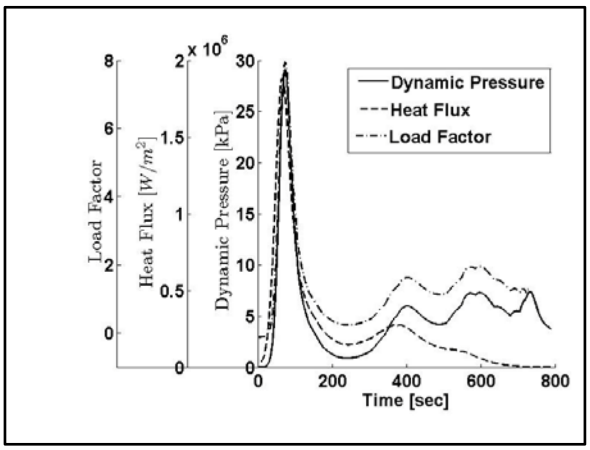

Fig. 5 : Dynamic Pressure, Heat Flux and Load Factor[2] variation with Time

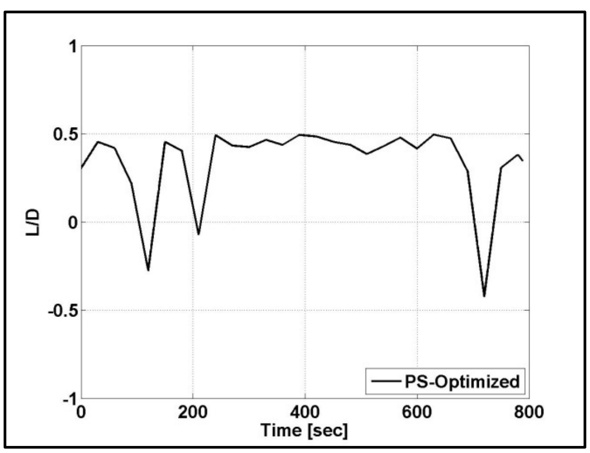

Fig. 6 : L/D variation with Time

It is noted that, up to ~34 sec the dynamic pressure is within 1kPa. During initial time of reentry, due to the very low dynamic pressure (at the higher altitudes), rate of altitude is mainly driven by the gravity component rather than Lift or Drag. Therefore it must be noted that, Values of L/D are insignificant up-to this point of time.

Further, it is noted that, the high dynamic pressure resulted in the high deceleration and heat flux around at ~74 sec at an altitude of ~54 km. However, during the simulation it is observed that the 8g deceleration constraint was effective during this time and subsequently PS evolved the L/D profile to overcome this bottle neck.

PS has evolved L/D such that, the flight path angle is maintained nearly zero to achieve the desired range up to the 500 sec. Later over ~150 sec flight path angle reduces gradually. In the last lap of the time (i.e. after 650 sec), since almost it has reached to the desired range, flight path angle is drastically decreased to achieve the desired terminal value.

The L/D variation has 28 discrete grid points each of 30 sec time step. The variation of the L/D is accepted. However, it is the matter of detail to further increase the grid points to achieve comparatively smoother L/D variation.

Integrated heat load term in the objective function :

Integrated heat load is added to the fore mentioned objective function and subsequently appropriate weights are redefined.

$$J = K1 * (r_d - r_f)^2 + K2 * (\gamma_d - \gamma_f)^2$$

$$+ K3 * (V_d - V_f)^2 + \int_0^t \dot{h}_f$$

Where,

$K1 = 10$; $K2 = 3.28280654\times10^{12}$; $K3 = 4\times10^{7}$

Convergence for this simulation is of the same order as previous and terminal states are achieved well within the acceptable limits. Fig. 7 to Fig. 11 shows the comparison of vehicle dynamics characteristics with and without integrated heat load term in the objective function.

Observations :

- Flight time is reduced by ~ 37.9 sec
- Altitude variation with Range is marginal.
- Comparatively lower velocities especially around 700 sec to accommodate the terminal conditions with less time.

[2] Load Factor shown in the plot is multiplied by -1.

- Peak heat loads are reduced. However, the total integrated heat load value is of the same order.
- Flight path angle is in similar trend in correspondence to respective total flight time.
- L/D profile shows comparatively smoother variation.

In order to minimize the heat load, PS has evolved L/D profile such that, the total time of flight and peak heat flux are reduced.

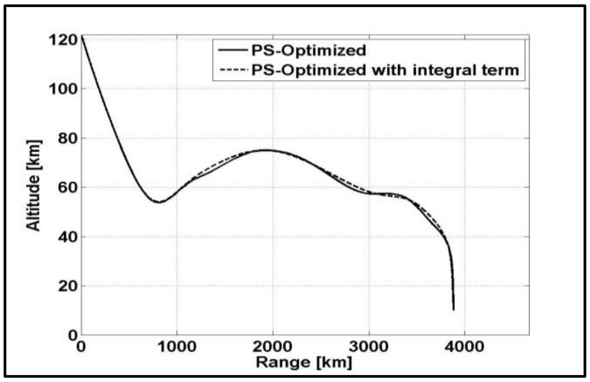

Fig. 7 : Altitude variation with Range

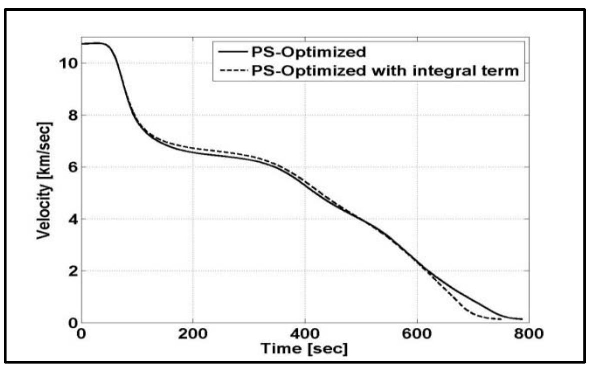

Fig. 8 : Velocity variation with Time

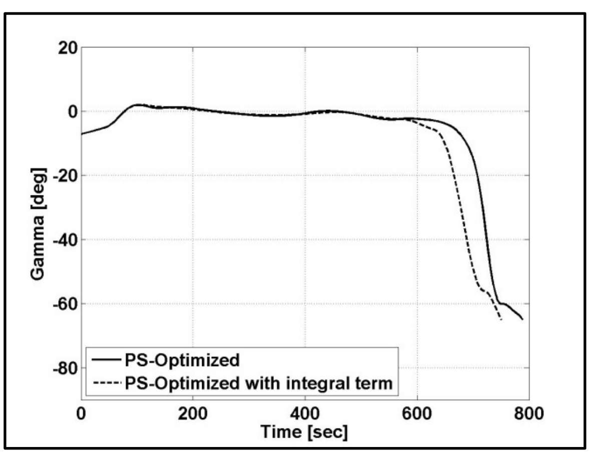

Fig. 9 : Flight Path Angle variation with Time

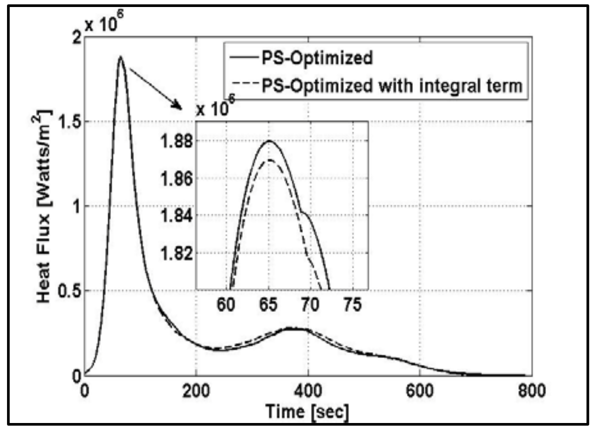

Fig. 10 : Heat Flux variation with Time

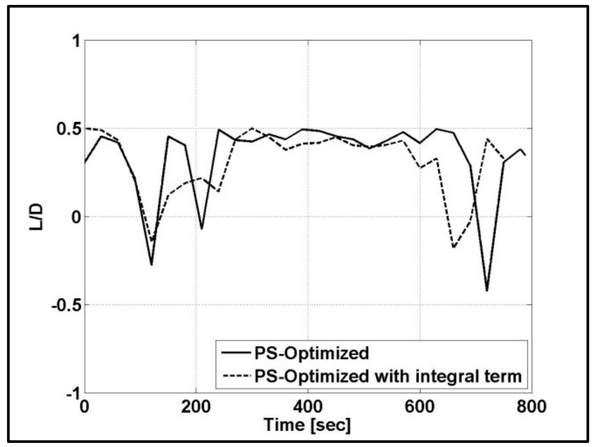

Fig. 11 : L/D variation with Time

5. CONCLUSIONS

Nonlinear constrained trajectory optimization problem is solved using Pattern Search technique. Aerodynamic performance 'L/D' is used as the control parameter. This formulation could effectively be used in preliminary trajectory design.

Comparison of with and without integrated heat load terms are presented. Results agree with the expected trends. Optimized L/D profile with integrated heat load term in objective function leads to comparatively smoother L/D variation.

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