

TRAJECTORY OPTIMIZATION OF HYPERSONIC GLIDER VEHICLE

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in

AERONAUTICAL ENGINEERING

By

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of Mr.SAKSHAR GHOSH (38260037) and Mr.SHAILESH KUMAR (38260038) who carried out the project entitled “**TRAJECTORY OPTIMIZATION OF HYPERSONIC GLIDE VEHICLES**” under our supervision from September 2020 to April 2021.

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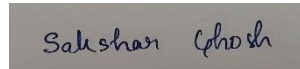
We, **SAKSHAR GHOSH (38260037)** and **SAILESH KUMAR (38260037)** hereby declare that the Project Report entitled “**TRAJECTORY OPTIMIZATION OF HYPERSONIC GLIDER VEHICLE**” done by us under the guidance of MADHAN KUMAR SIR is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in AERONAUTICAL ENGINEERING

DATE : 05.05.2022

PLACE : CHENNAI

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ABSTRACT OF THE PROJECT

On the basis of the analysis of the hypersonic glider vehicle trajectory, the Multiobjective Trajectory Optimization Problem (MTOP) is formulated. By using the boundary intersection method and pseudospectral method, the MTOP is reduced to a set of general optimization subproblems. A nonlinear programming algorithm is used to solve the subproblems. This is an area of Multiple Criteria Decision Making, which consists of identifying multiple objective functions that must be optimized simultaneously. In a multiobjective trajectory optimization problem, the pseudospectral method is combined with the boundary intersection method to convert it into a collection of single-objective optimization problems, and finally, each of these problems is solved individually with the pseudospectral method. There is no easy solution to the problem of optimizing multiple objectives simultaneously with nontrivial multi-objective optimization. A conflict between the objective functions is said to exist in that case. If none of the objective functions can be improved in value without affecting the value of some of the other objectives, it is termed nondominated, Pareto-optimal, Pareto-efficient, or noninferior. A (possibly infinite) number of Pareto optimal solutions may exist even without additional subjective preference information. When it comes to setting and solving multi-objective optimization problems, different philosophies and objectives are used by researchers. There may be a desire to determine the Pareto optimal set of solutions and/or to quantify the trade-offs between different objectives.

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LIST OF SYMBOLS

C_l	Coefficient of Lift
C_d	Coefficient of Drag
C_m	Coefficient of Moment
ρ	Density
A	Area
V	Velocity
L	Lift
AR	Aspect Ratio
E	Efficiency Factor
α	Angle of Attack
γ	Flightpath angle
v_0	Initial velocity
r	Nose radius

CHAPTER 1

INTRODUCTION

1.1 **HYPERSONIC GLIDER**

One of the major factors separating 'hypersonic' missiles from other missiles is their high speed. While ballistic missiles often travel at speeds far exceeding those of today's hypersonic missiles, their range is much greater. The A-4 was the ancestor of ballistic missiles and was developed in Germany in the 1940s. On the way up, it could reach a speed greater than Mach 5 and, briefly, on the way down, it could also reach that speed. However, no one would claim that the V-2 was a hypersonic missile.

Due to their high velocity and maneuverability, hypersonic weapons are further classified into two separate types of missiles: hypersonic cruise missiles (HCMs) and hypersonic glide vehicles (HGVs). During the entire course of their flight, HCMs maintain a constant speed (and usually altitude). Contrary to HGVs, ballistic missiles typically launch them on top of missile boosters before gliding back to target at hypersonic speeds through the atmosphere.

1.1.1 **SUBSYSTEMS FOR HYPERSONIC GLIDE VEHICLES**

HGVs are designed to fly precisely into a target, regardless of whether they carry conventional, nuclear, or no payload. In order for a vehicle to maintain some level of autonomy, sensors and computation are required. Thus, an HGV needs most of the same (or at least similar) basic subsystems as a missile, except for its propulsion system. HGVs, which

are launched on rocket boosters, glide to their destinations without needing a main engine since they launch on rocket boosters.

The main subsystems of an HGV are guidance and control system, a lightweight airframe, and the payload

1.2 Trajectory Optimization Problem

In trajectory optimization, one aims to minimize or maximize a certain measure of performance while satisfying a set of constraints. An open-loop solution to an optimal control problem is computed using trajectory optimization. The method is often used for systems where it is impractical or impossible to compute a complete closed-loop solution. In order to generate a closed-loop solution in the sense of Caratheodory, a trajectory optimization problem can be solved iteratively by inverse Lipschitz constant. An infinite-horizon problem is model predictive controlled (MPC) if only the first step of the trajectory is executed.

It has been possible to calculate variations of trajectory for hundreds of years, but only with the advent of a computer has it become practical for real-world problems. Originally, trajectory optimization was used in aerospace to compute the trajectories of rockets and missiles. The use of trajectory optimization in industrial processes and robotics has also increased recently.

1.2.1 Overview Of Single Objective Function

By using a single objective problem optimization method of the hybrid MED + RO process, the operating pressure, flow rate, and temperature of the RO process were increased in comparison to the base case of not optimised operating conditions. This confirms the hybrid system's ability

to reduce its energy consumption by 25%. An increase in the amount of high-quality water produced which meets the demands of generating large volumes of fresh water can be credited with the reduction in energy consumption.

1.2.2 Overview Of Multi-Objective Function

A multi-objective optimization problem is one in which there is more than one objective function to be optimized simultaneously in a decision-making process based on multiple criteria. Multi-objective optimization refers to mathematical optimization problems involving the simultaneous optimization of more than one objective function. The goal of maximizing performance while minimizing fuel consumption and pollutant emissions of a vehicle is an example of a multi-objective optimization problem involving two objectives, and maximizing comfort while minimizing cost during car purchase is an example of a three-objective optimization problem. A practical problem may have more than three objectives.

CHAPTER 2

LITERATURE SURVEY

2.1 LITERATURE SURVEY FOR OPTIMIZATION CONTROL

2.1.1 Spacecraft Trajectory Optimization by Bruce A. Conway

(Bryson, A. E., and Ho, Y-C. (1975) *Applied Optimal Control*, Hemisphere Publishing Co., Washington DC)

OBJECTIVE	METHODOLOGY	RESULT/INFERENCE
An Optimal Impulsive Trajectory Using Primer Vector Theory	An optimal trajectory can be derived using the calculus of variations, a generalization of optimal control.	Primer vector theory pertains to impulsive trajectories, which is the most completely developed. The addition of midcourse impulses and terminal coasting periods can sometimes reduce the cost of fixed-time trajectories. Modifications to the primer vector are indicated by the primer vector. The first gradients of cost along terminal impulse times as well as

		midcourse impulse times and positions were calculated by Lion and Handelsman.
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2.1.2 John T. Betts Practical Methods for Optimal Control

Reference link:- <https://doi.org/10.1137/1.9780898718577>

OBJECTIVE	METHODOLOGY	RESULT/INFERENCE
This course presents the background in nonlinear programming methods relevant for estimation using nonlinear programming.	The original edition presented information in a concise and focused manner. This book describes how differential algebraic equations can be discretized using sparse optimization methods. The original edition presented information in a concise and focused manner. The book explains how sparse optimization methods may be combined.	Interested readers can license SOCS software from Boeing to receive the code referenced within the book.

2.1.3 REFERENCE FOR TRAJECTORY PLANNING

Proceedings of the IMechE, Part G: Journal of Aerospace Engineering

R Zardashti, AA Nikkhah, MJ Yazdanpanah

“Multi-objective trajectory planning over terrain using the label-setting greedy-based algorithm ”

Using an unmanned aerial vehicle on a low elevation for threat avoidance/trajectory mission, this paper studies the multi-objective trajectory planning problem. With the help of a grid-based discrete method, continuous constrained optimization problems are transformed into a mixture of search and choice problems over finite networks. A label-setting greedy-based algorithm is then applied to this problem as a variant of the minimum cost network flow approach. A four-dimensional trajectory from a source to an endpoint is determined deterministically using digital ground elevation data and discrete dynamic comparisons of motion by lessening a nonlinear cost function based on the dynamic and mission constraints of the unmanned inflight vehicle. Cost functions are calculated by combining the length of the path, the fuel consumption, the flight time, and the risk-of-threat area for each arc in the grid. Further, for these types of vehicles, having a safe flight at low altitude and avoiding collisions with terrain is an issue due to the increasing deviation of inertial navigation systems over time.

2.1.4 Three-Dimensional Offline Path Planning for UAVs Using Multiobjective Evolutionary Algorithms

Shashi Mittal and Kalyanmoy Deb

It is primarily future to develop a path planning system for UAVs on an offline basis. This kind of path planner can be used to navigate drones over rough terrain, where piloting the terrain might be difficult and disposed to to accidents. Often, the length of such a route is minimized or the safety boundary against ground obstacles is maximized through plan of an optimization problem. It is yet a true multi-objective optimization problem, since both minimizing the distance travelled and concurrently maximizing safety margins can be important simultaneously. In no past study has the path planning problem been considered as a multi-objective optimization problem.

2.1.5 Variational Technique for Spacecraft Trajectory Planning

Carl Glen Henshaw and Robert M. Sanner

The paper discusses a spacecraft trajectory planning algorithm based on the calculus of variations that can handle docking and proximity operations for spacecraft with six degrees of freedom. The concept of designing a cost function that balances fuel use, obstacle clearance distance, and arrival time is discussed. Dynamical constraints are applied to nonlinear orbital dynamic equations. We derive the Euler-Lagrange equations for this functional and describe the Pontryagin criteria for the optimal control inputs under saturating on-off thruster conditions. A lack of sensitivity to initial conditions encourages the use of indirect collocation in solving the boundary-value problem; continuation further improves the algorithm's robustness.

2.2 LITERATURE SURVEY FOR BOUNDARY INTERSECTION METHOD

2.2.1 Normal-Boundary Intersection: A New Method for Generating the Pareto Surface in Nonlinear Multicriteria Optimization Problems

The paper provides an alternative method for finding several Pareto optimal points for a nonlinear multicriteria optimization problem. Collectively, these points represent the trade-off among the various competing objectives. In contrast to the popular method of minimizing weighted combinations of objective functions, this method produces an evenly distributed set of points in the Pareto set regardless of the relative scales of the functions. Furthermore, the continuation-type method retains its efficiency while handling more than two objectives. The trade-off curve can now be traced more easily than with conventional continuation techniques since conventional continuation methods are difficult to extend to handle more than two objectives.

2.2.2 Improved normal-boundary intersection algorithm:

Increasingly, smart buildings are outperforming traditional buildings due to the wide use of distributed energy sources. Due to these factors, its energy optimization scheduling and multi-objective optimization have become increasingly complex and must be resolved on an urgent basis. The paper presents an innovative method for optimizing energy consumption in smart buildings. In order to evaluate distributed renewable energy, several transfer-retention ratio (TRR) parameters are added. A second improvement to the normal boundary intersection (NBI) algorithm is incorporating the adaptive weight sum, the adjustment of uniform axes, and the Mahalanobis distance. To increase the efficiency of regulation in smart buildings, parameters TRR and INBI are used to improve the multi-objective optimization problem. According to the criteria for the evaluation

of decision-makers, the average deviation has been reduced by 60% from the previous case. Three optimization objectives illustrate how the proposed method is superior to existing methods. There are also objectives to reduce equipment costs by 8.2%, to reduce power supply costs by 7.6%, and to improve occupant comfort by 1.6%.

CHAPTER – 3

AIM AND SCOPE OF THE PROJECT

Hypersonics refer to flight at speeds exceeding five times the speed of sound, or Mach 5 (3,800 mph or 6,100 km/h). Hypersonic flight brings with it a set of engineering considerations that supersonic craft are not required to deal with. The craft produces shock waves and frictional heating is one method to control them. Hypersonic vehicles also generate shockwaves that are closer to the craft than supersonic ones do. There are many kinds of craft that can operate in the hypersonic regime - for instance, a hypersonic cruise missile which soars through the upper atmosphere using a ramjet. The hypersonic glide vehicles, however, ride to orbit with conventional boosters before deorbiting and gliding through the atmosphere to their target. In essence, HGVs are spacecraft. In this way, they resemble rocket-launched spaceplanes, like the Air Force's X-37B, which launches into orbit, returns to earth, and lands on a runway after reentering the atmosphere. A major focus of our research is all aspects of hypersonic flight, notably in terms of complex constraints, such as aerodynamic heating. In order to optimize the trajectory of hypersonic glide vehicles, we optimized the nose cone radius. The project is mainly based on Matlab G.A. which is used to solve the multi-objective trajectory optimization problem in relation to the given conditions.

CHAPTER 4

DESIGN AND METHODOLOGY

4.1 Design

With the help of Solidworks design software we designed our own hypersonic glider based on current designs under development in multiple countries such as China and Russia. A certain amount of pressure and velocity is intended to be absorbed by the design.

The hypersonic glide vehicle designs designed by us are as follows:-

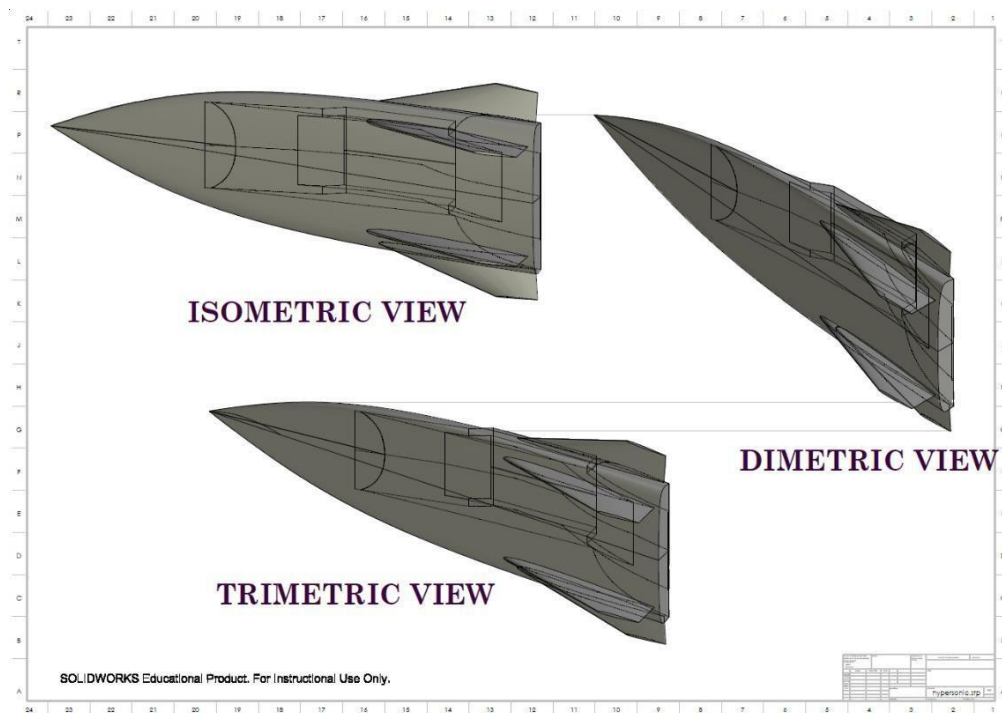


Fig :- ISOMETRIC , DIMETRIC AND TRIMETRIC VIEW

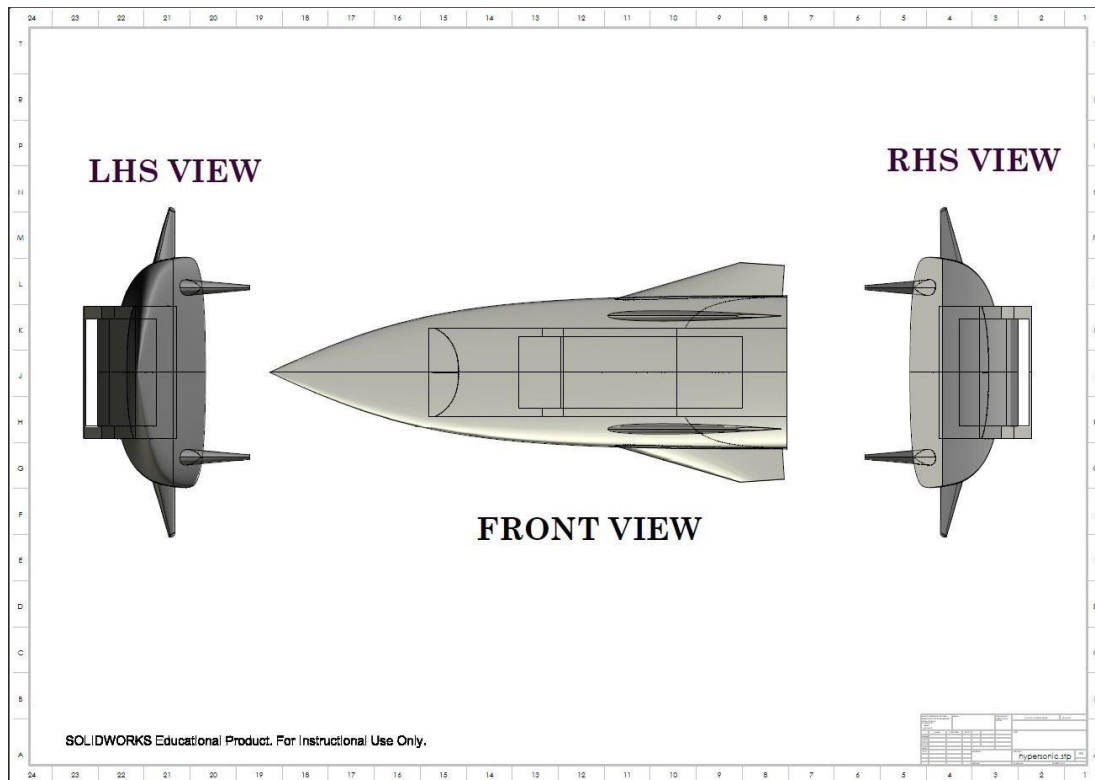


FIG :- LHS , FRONT AND RHS VIEW OF HGV

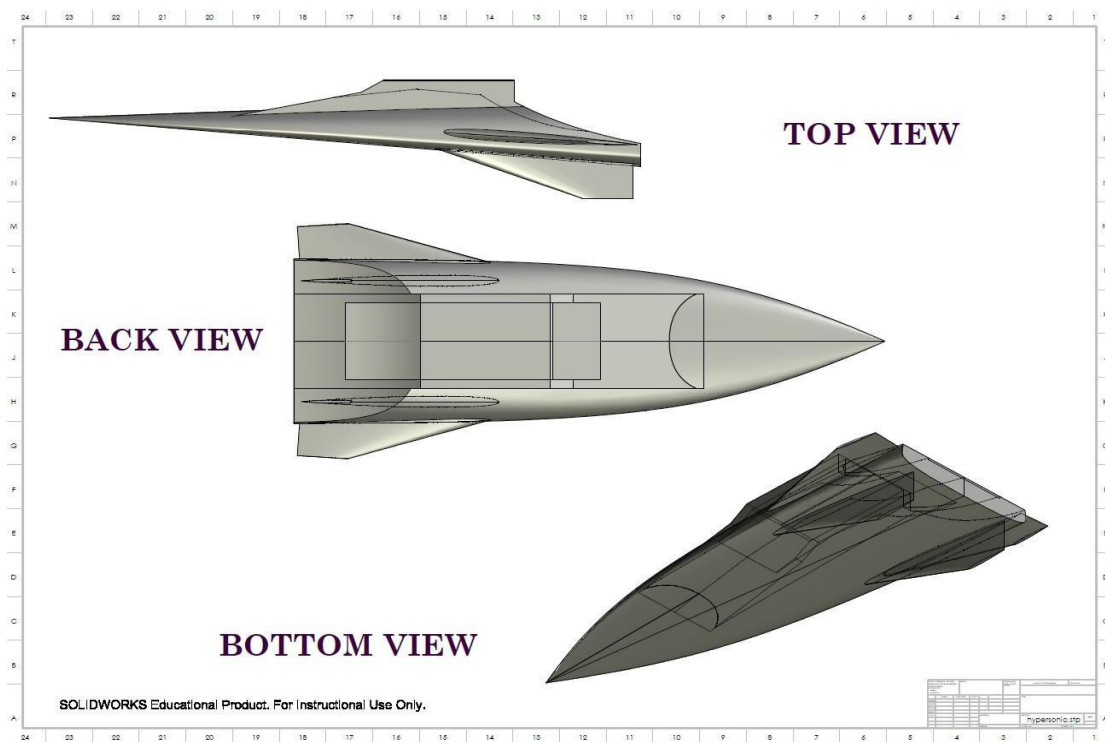
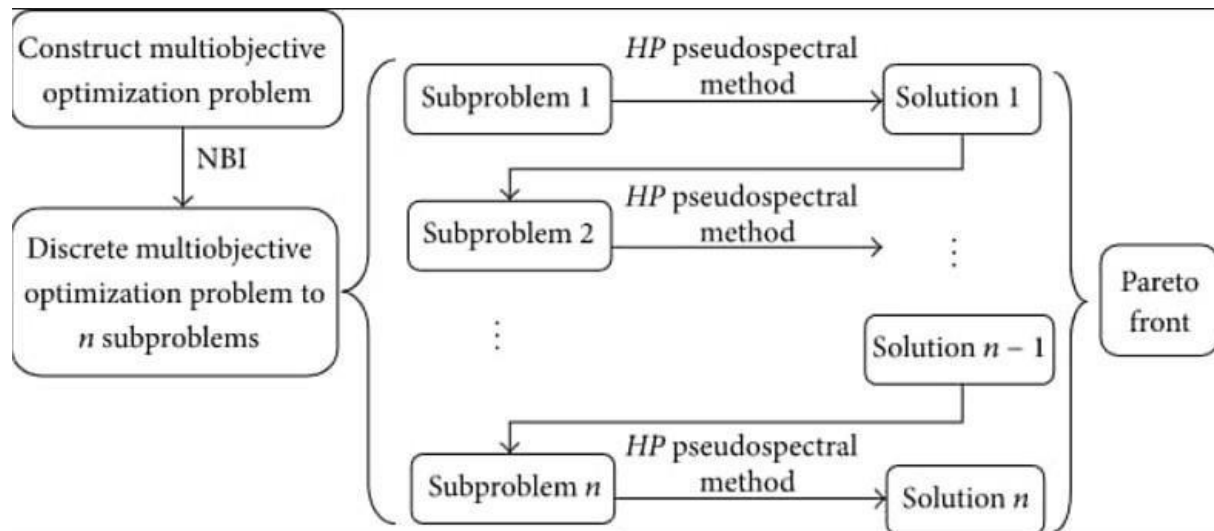


FIG:- TOP, BACK AND BOTTOM VIEW OF HGV

4.2 Matlab Optimization

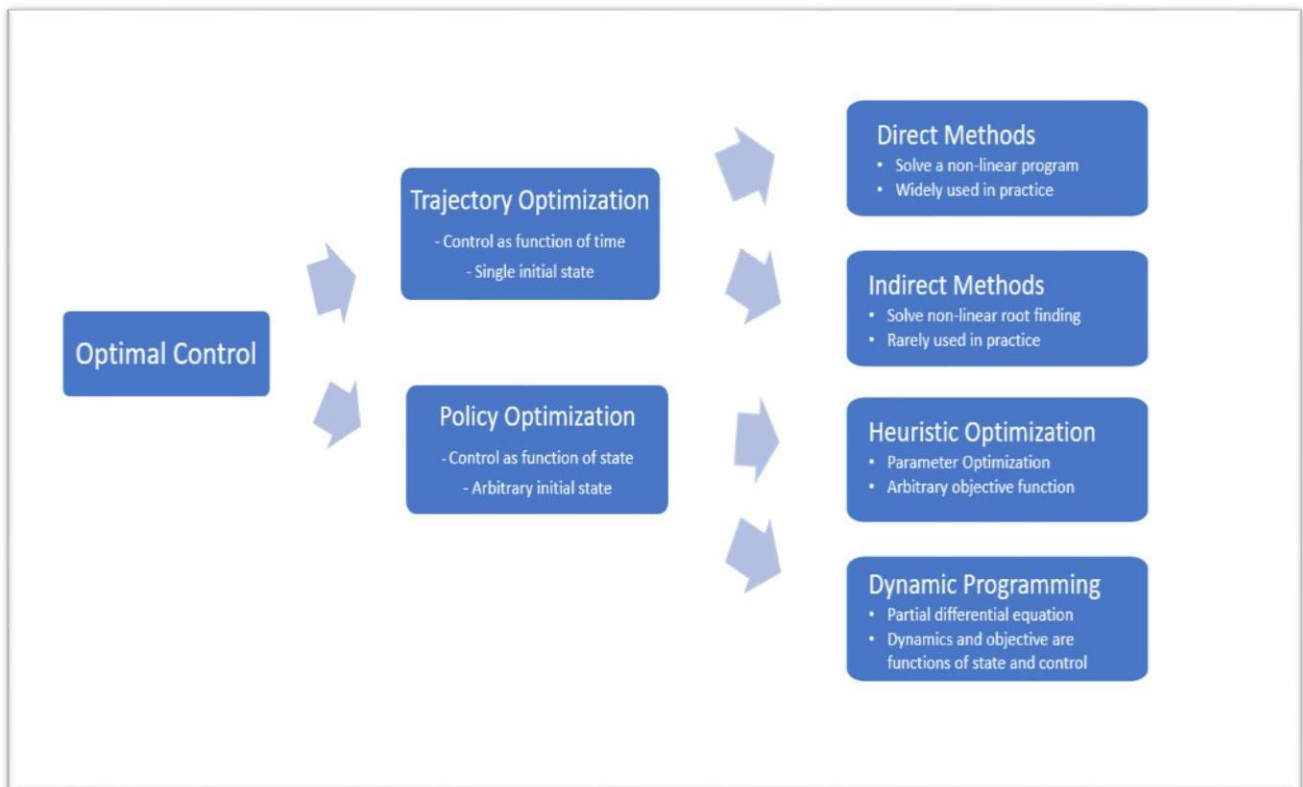
The below block diagram shows the basic working of Trajectory Optimization Problem:-



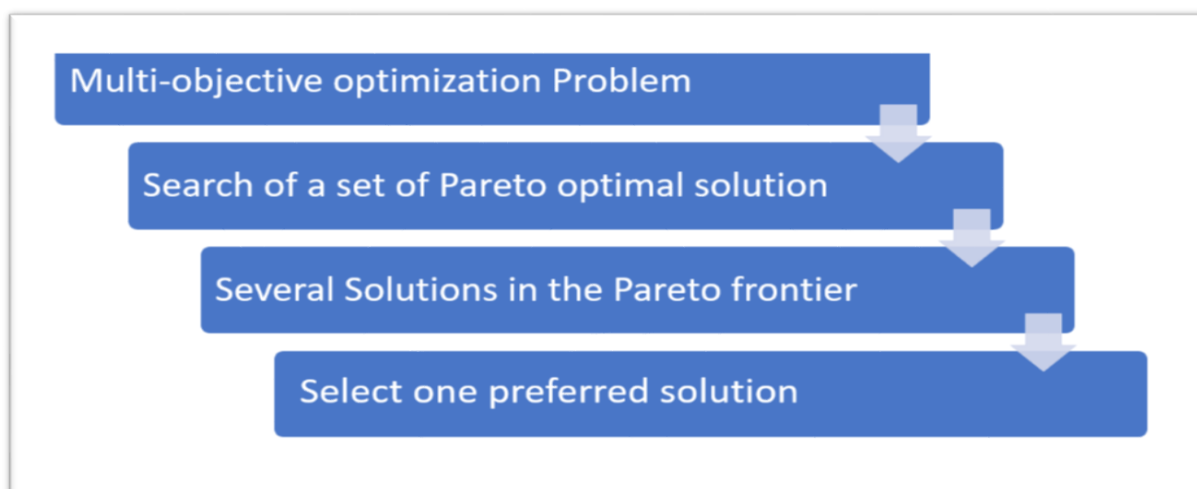
An example of Multi-Objective Optimization is presented in the above diagram using a GA solver in Matlab that uses HP pseudospectral method.

A Genetic Algorithm (GA) mimics the evolutionary process of natural selection by solving both constrained and unconstrained optimization problems. By using biologically inspired operators such as mutation, crossover, and selection to modify a population of individual solutions over time, genetic algorithms can generate high-quality solutions to optimization and search problems.

4.2.1 GENERAL PROCESS OF FINDING THE PARETO SOLUTION:-



Heuristic Optimization Method is used here for trajectory optimization, where solutions are determined by pareto sets.



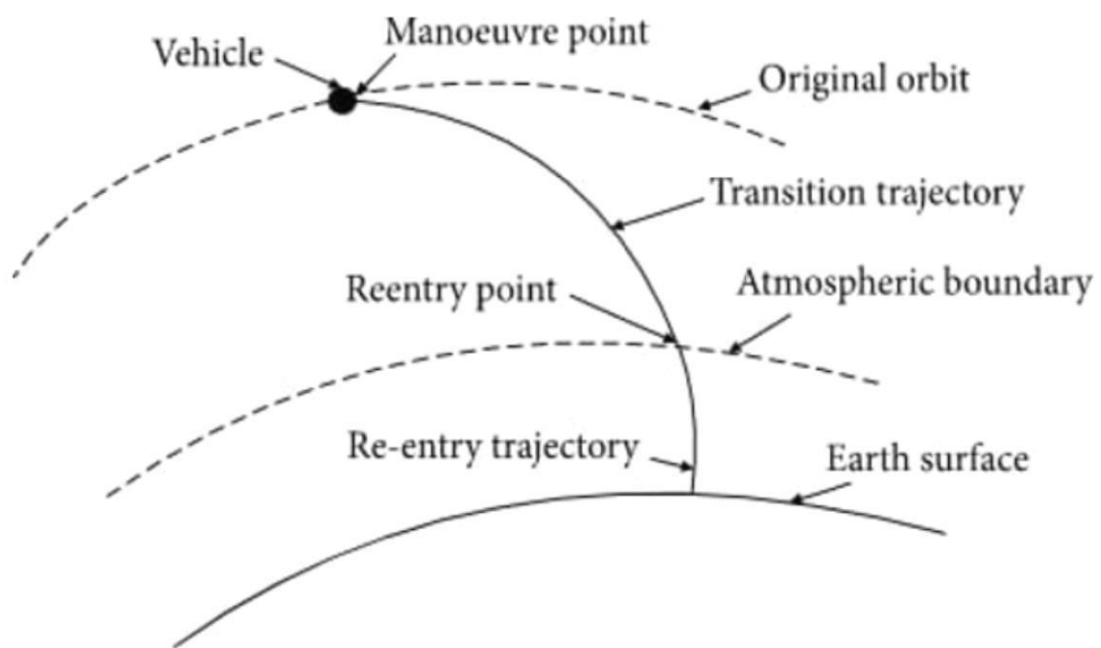


Fig :- phases of re-entry

4.3 BASIC NATURE AND PATH OF A HYPERSONIC GLIDE VEHICLE

The Hypersonic Glide Vehicle (HGV) is shown in the figure below to follow a fixed trajectory. The trajectory is pre-determined and the vehicle can make minor corrections before re-entering the atmosphere.

Re-entry phases have been depicted in the above figure. Typical low earth re-entry speed: **17,500** mph. Escape velocity for glide vehicle to enter orbit from earth around **25,000**mph.

CHAPTER 5

TRAJECTORY OPTIMIZATION FORMULAE AND RESULTS

5.1 FORMULAE USED FOR MATLAB PROGRAMME :-

$$\text{Lift coefficient } C_L(\alpha) = a_0 + a_1\alpha$$

$$\text{Drag coefficient } C_D(\alpha) = b_0 + b_1\alpha + b_2\alpha^2$$

$$\text{stagnation heat flux } q = q_a(\alpha)q_r(h, V),$$

$$q_a(\alpha) = C_0 + C_1\alpha + C_2\alpha^2 + C_3\alpha^3$$

$$q_r(h, V) = 2.01 \times 10^8 \sqrt{\rho} \times (10^{-4} V)^{3.07}$$

Here coefficients of lift and drag are used with stagnation heat flux to determine Pareto solution .

The variables taken into consideration are :

- Flight path angle (Y)
[Range between 10.454 to 12.354]
- Initial velocity (v_0)
[Range between Mach 25 to Mach 45]
- Nose radius (r)
[Range between 0.5 to 0.9]

5.2 Proposed Procedure

5.2.1 The steps of the algorithm are enumerated

Step 1: The Pareto-optimal curves are obtained by using an evolutionary multi-objective optimizer.

Step 2: Genetic algorithms selected about 30 well-distributed solutions from the set of Pareto-optimal solutions, so that the selected solutions provide a good trade-off between the objectives.

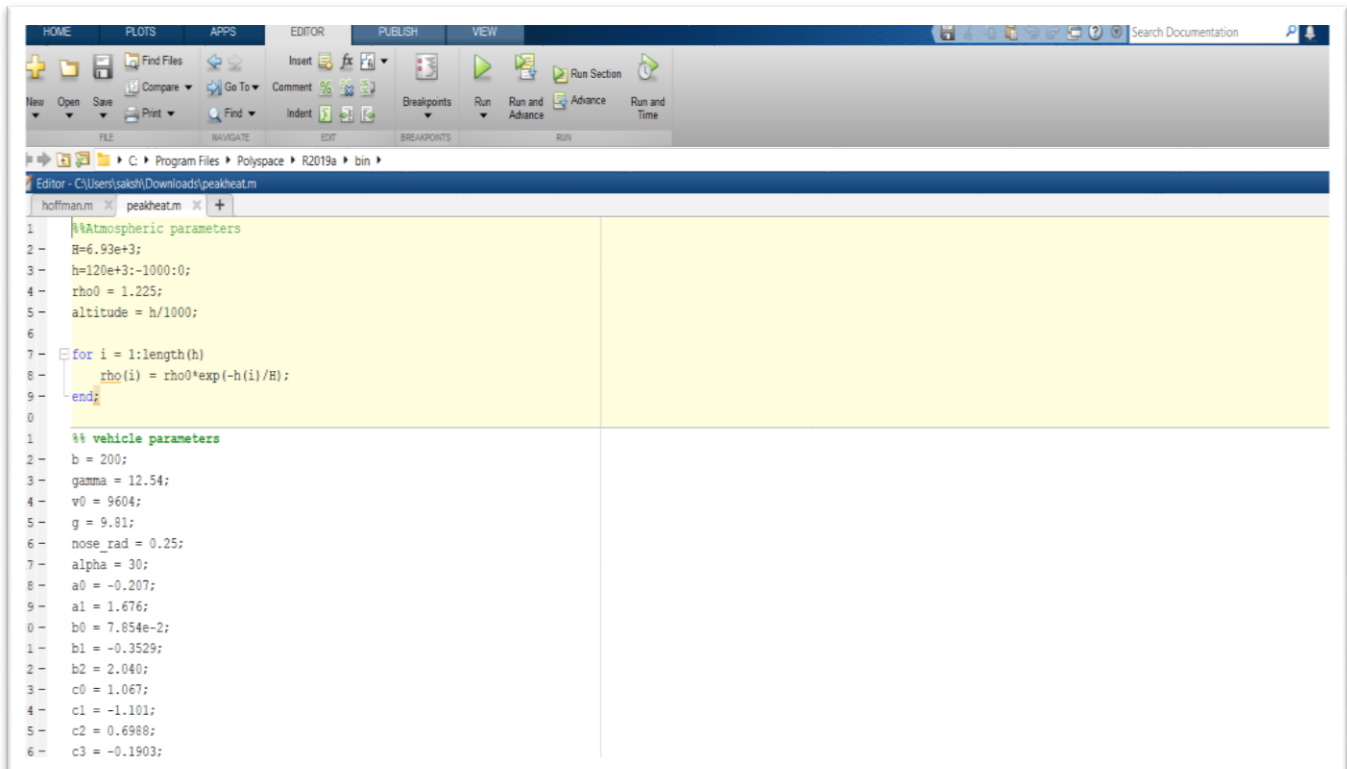
Step 3: The solutions are then subjected to a local search to ensure that they are close to the true Pareto-optimal solution.

5.2.2 Constraints:-

The optimization problem is subject to the following three constraints

1. When flying over the terrain, the vehicle cannot collide with the boundary.
2. HGVs shouldn't make abrupt direction changes. In order to enforce this constraint, we require the angle between two successive segments of be greater than a particular cut-off angle.
3. There should not be a point in the curve that is higher than a specified maximum height.

5.2.3 RUNNING AND OPERATION OF THE MATLAB CODE :-The matlab code is successfully executed with the help of optimization tool .



```

1 %%Atmospheric parameters
2 H=6.93e+3;
3 h=120e+3:-1000:0;
4 rho0 = 1.225;
5 altitude = h/1000;
6
7 for i = 1:length(h)
8     rho(i) = rho0*exp(-h(i)/H);
9 end;
10
11 %% vehicle parameters
12 b = 200;
13 gamma = 12.54;
14 v0 = 9604;
15 g = 9.81;
16 nose_rad = 0.25;
17 alpha = 30;
18 a0 = -0.207;
19 a1 = 1.676;
20 b0 = 7.854e-2;
21 b1 = -0.3529;
22 b2 = 2.040;
23 c0 = 1.067;
24 c1 = -1.101;
25 c2 = 0.6988;
26 c3 = -0.1903;

```



```

%%aerodynamic coefficients
for k = 1:length(alpha)
    K = H/(2*b(k)*sind(gamma));
    for i = 1:length(altitude)
        cl(i,k) = K*(a0+a1*alpha(k))*(rho0/rho(i)-1);
        cd(i,k) = K*(b0+b1*alpha(k)+b2*(alpha(k))^2)*(rho0/rho(i)-1);
        Q(i,k) = (c0+c1*alpha(k)+c2*(alpha(k))^2+c3*(alpha(k))^3)*2.01e8*sqrt(rho(i))*(1e-4*gamma)^3.07;
    end;
end;

%%Reentry Loads
for j = 1:length(b)
    K = H/(2*b(j)*sind(gamma));
    for i = 1:length(altitude)
        n(i,j) = v0^2*exp(-2*K*rho(i))*rho(i)/(2*b(j)*g);
        g(i,j) = 1.83e-4*sqrt(rho(i)/nose_rad(j))*v0^3*exp(-3*K*rho(i));
        vr(i) = v0*exp(-K*rho(i));
    end;
end;

%%plots
figure(1)
plot(-n,altitude,'LineWidth',2);
set(gca,'FontSize',20);
xlabel('Deceleration (g)','FontSize',24);
ylabel('Altitude (km)','FontSize',24);

```

Considering the above matlab code seven graphs have been plotted with 30 different iteration value of the variables given.

The Graphs are as follows :-

- Altitude (km) vs Deceleration (g).
- Altitude (km) vs Stagnation point heating rate (MW/m^2).
- Altitude (km)vs velocity (KM/s).
- Altitude (km)vs Peak-heat (KN/m^2).
- Altitude (km)vs Lift-coefficient.
- Altitude (km)vs Drag-coefficient.
- Lift-coefficient vs Drag-coefficient.

The above mentioned graphs are then plotted and 30 iterations are taken.

These iterations are then considered for finding the minimum and the maximum value each of the given graphs and plotted in form of excel sheet.

5.3 RESULTS :-

The above mentioned graphs for 30 iterations are as follows:-

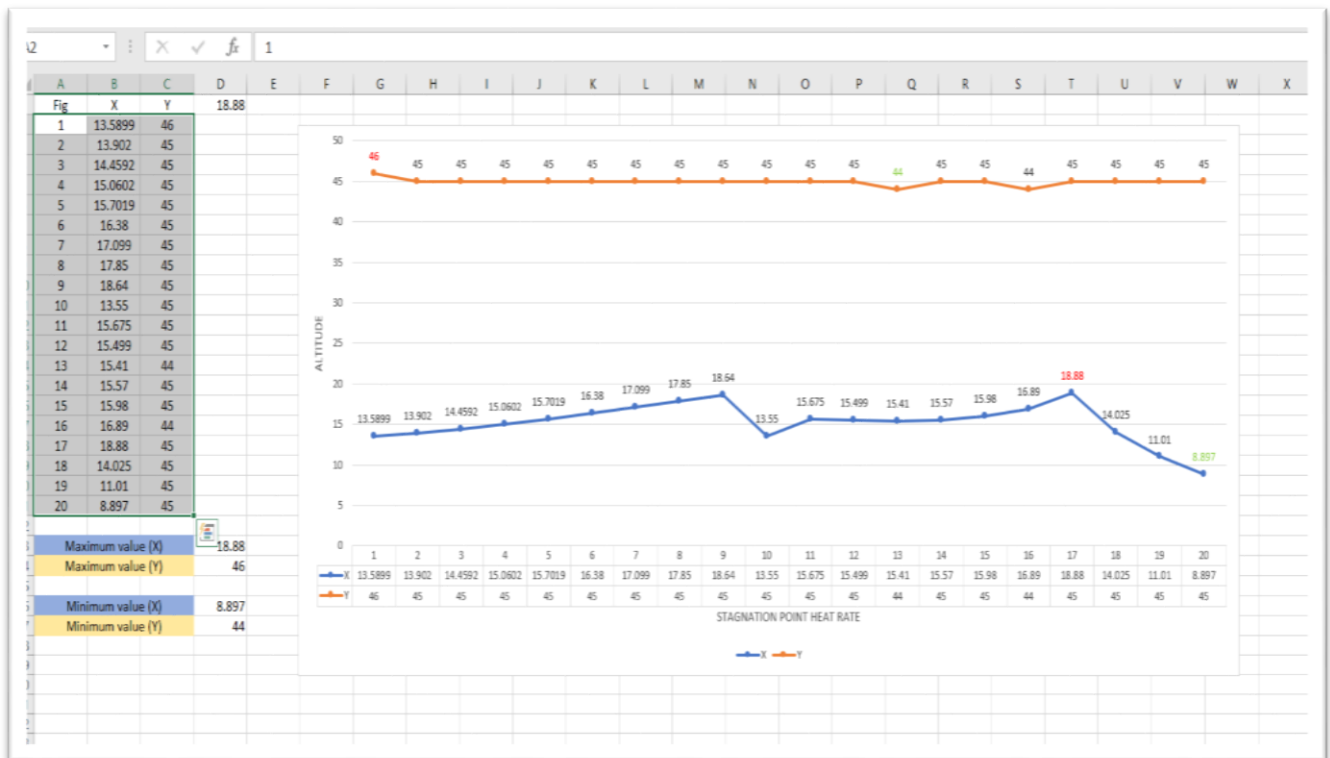


Fig: Altitude vs Stagnation point heat rate

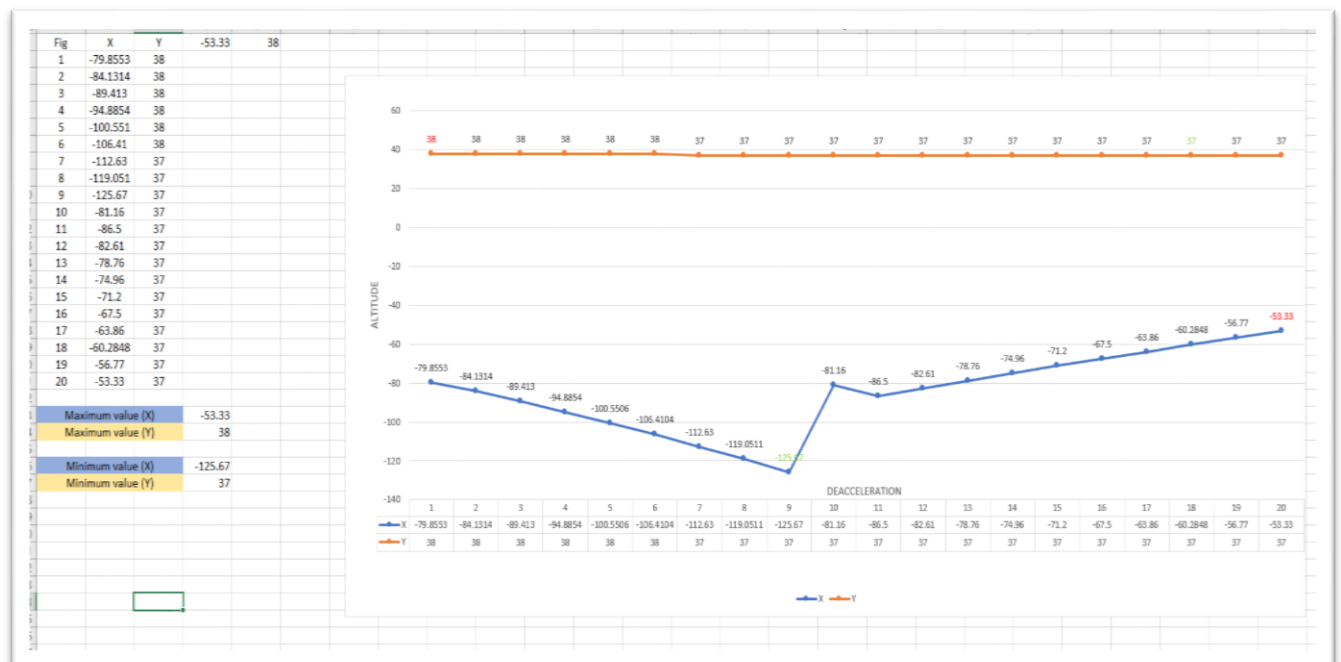


Fig: Altitude vs Deceleration

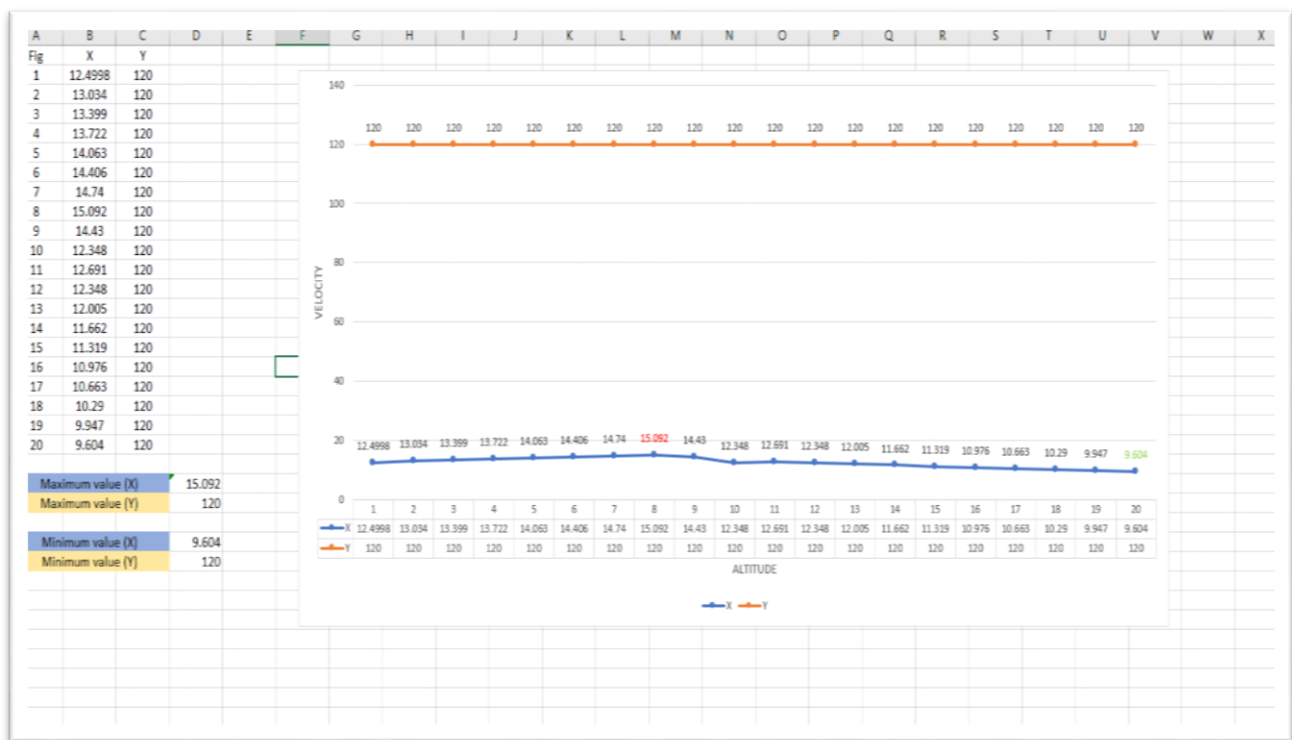


Fig: Altitude vs Velocity

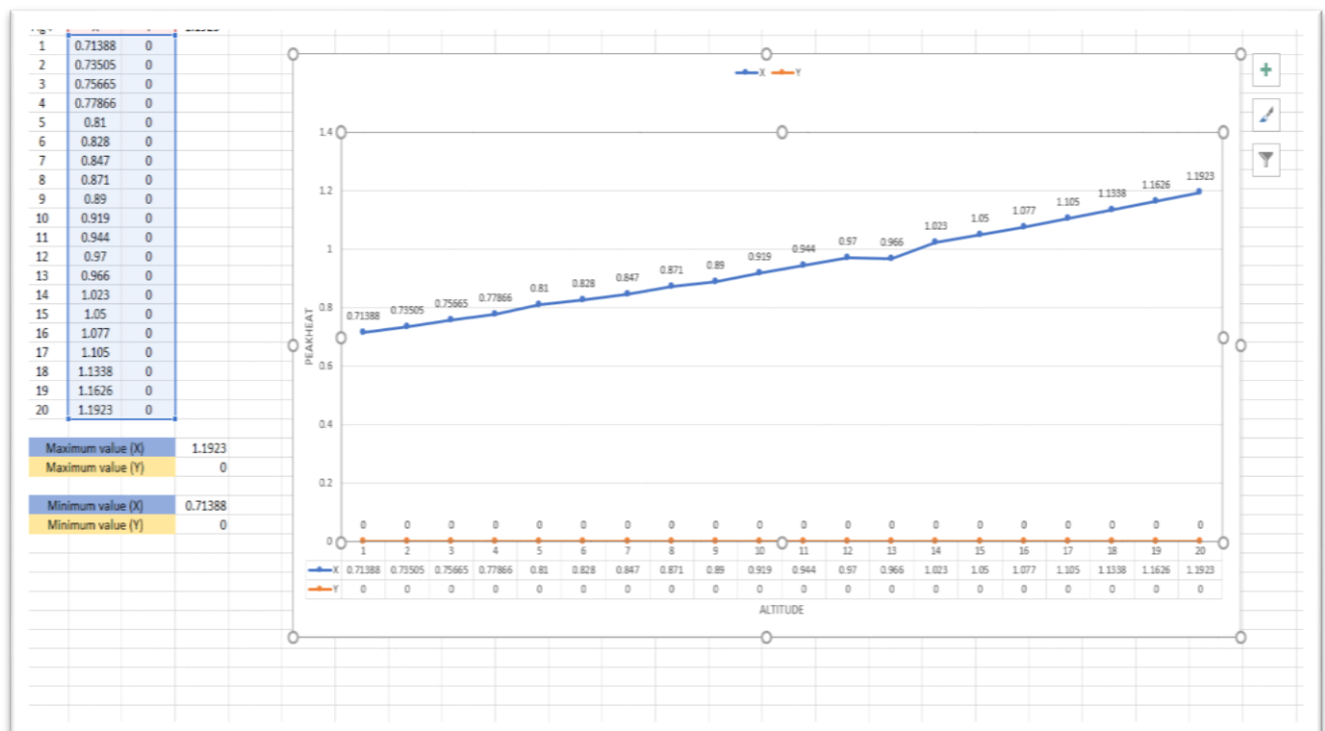


Fig: Altitude vs Peak-heat



Fig: Altitude vs Lift-coefficient

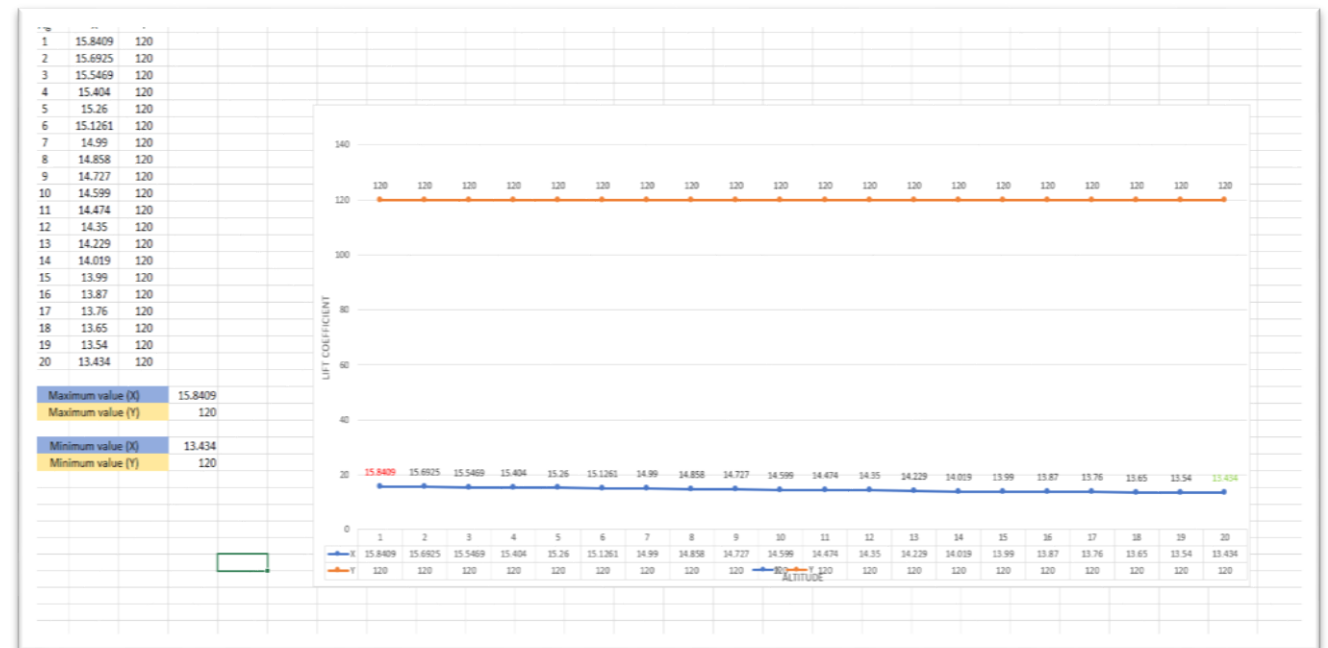


Fig: Altitude vs Drag-coefficient



Fig: Lift-coefficient vs Drag-coefficient

CHAPTER 6

FABRICATION AND ASSEMBLY OF THE MODEL

6.1 FABRICATION

The fabrication work of the model is done with the help of a 3D printer and using plastic as printing material. The hypersonic glider is 3D printed in two separate parts and then glued together for testing purpose. Tests were run in wind tunnel keeping the model in place.

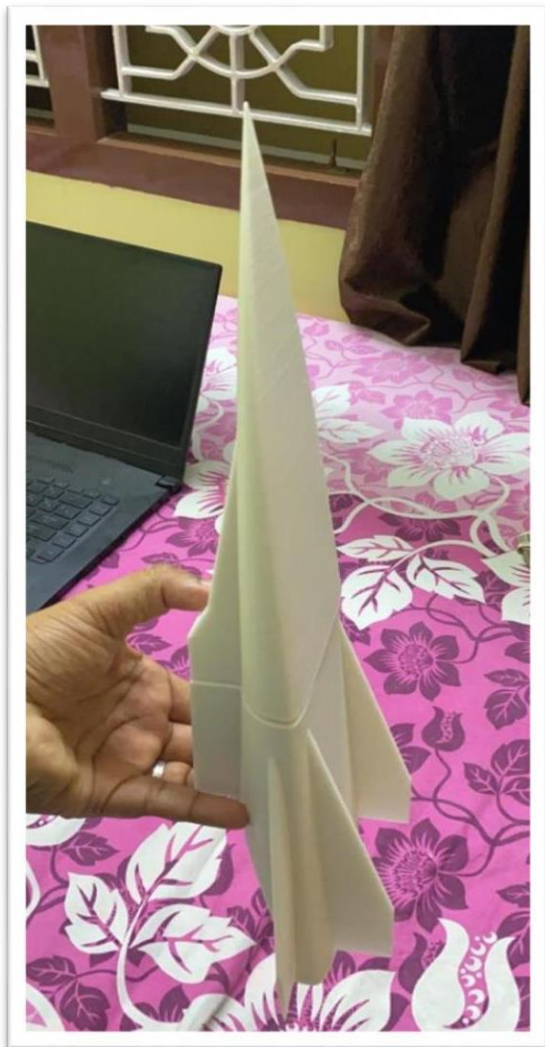


Fig:- Parts of the fabricated model

6.2 ASSEMBLY

The fabricated parts are then joined together by superglue and is finally assembled into shape of a glider. The assembled parts are then mended together with white cement.

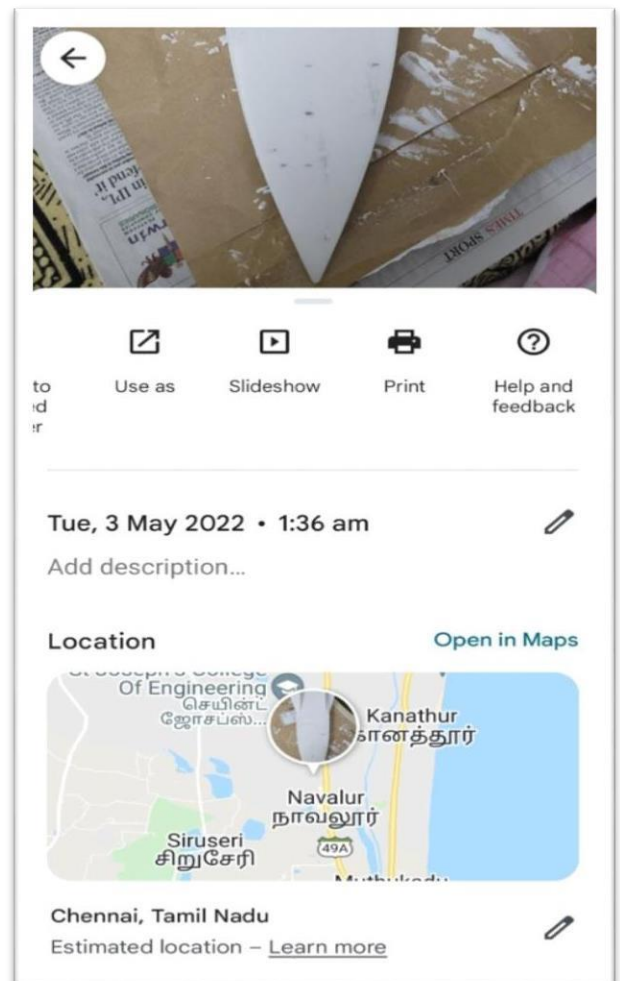
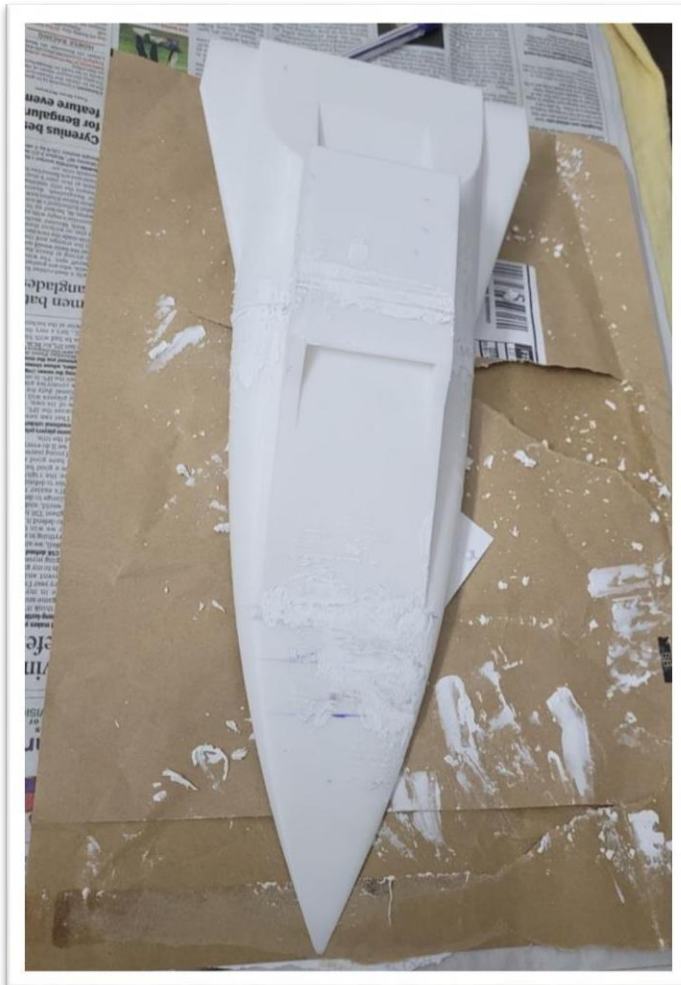


Fig:- Assembled model along with geotag pictures

CHAPTER 7

WINDTUNNEL TESTING

The following model is tested in windtunnel with the guidance of our guide and taking angle of attack into consideration to find the experimental data.

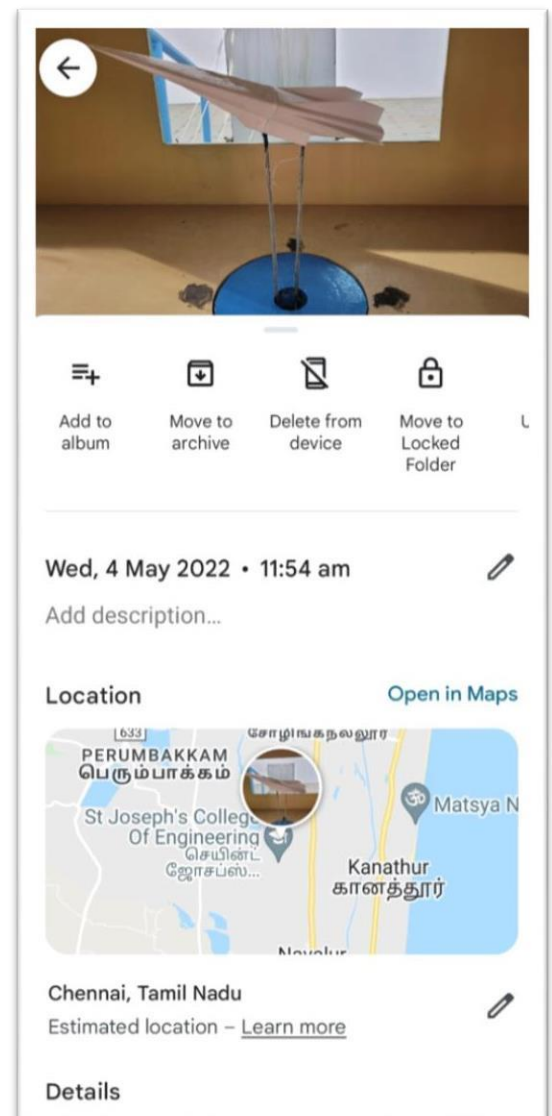


Fig:- Wind tunnel testing in Aerodynamics lab with geotag pictures

7.1 Instrument Used

Six component strain gauge balancing is used to determine lift and drag values as well as finding the L/D ratio.

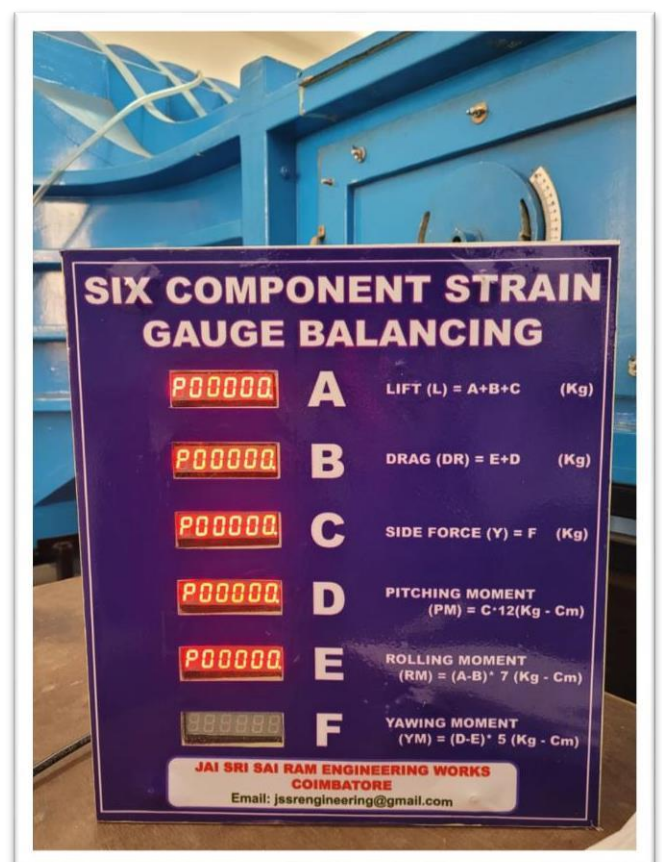
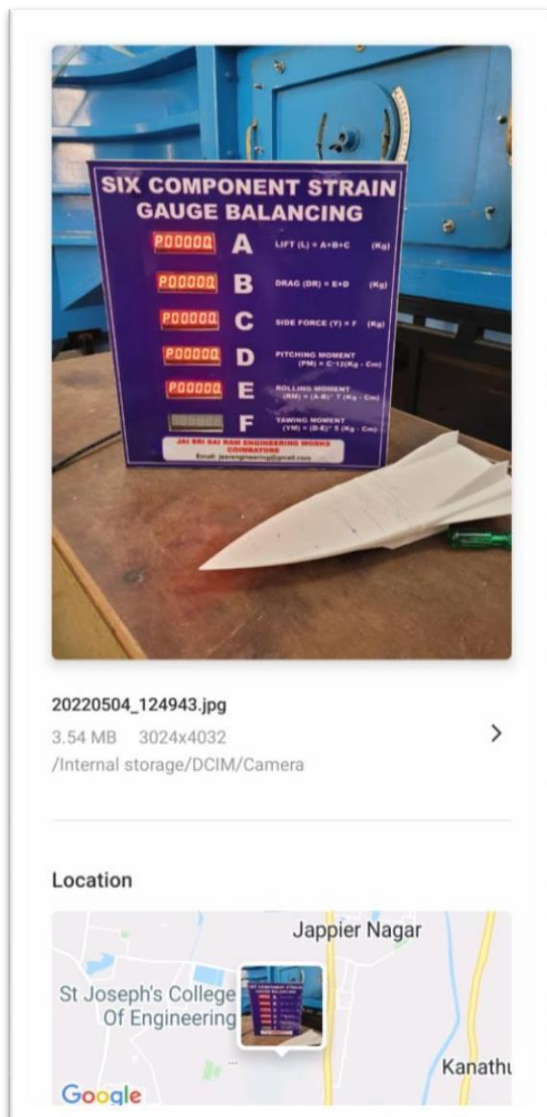


Fig :- Instrument for measuring the values

7.2 Comparison of lift and drag in Incompressible flow

The testing is thus concluded as we compared the valued of lift and drag coefficient in case of hypersonic flow and thus the wind tunnel testing is successfully completed.

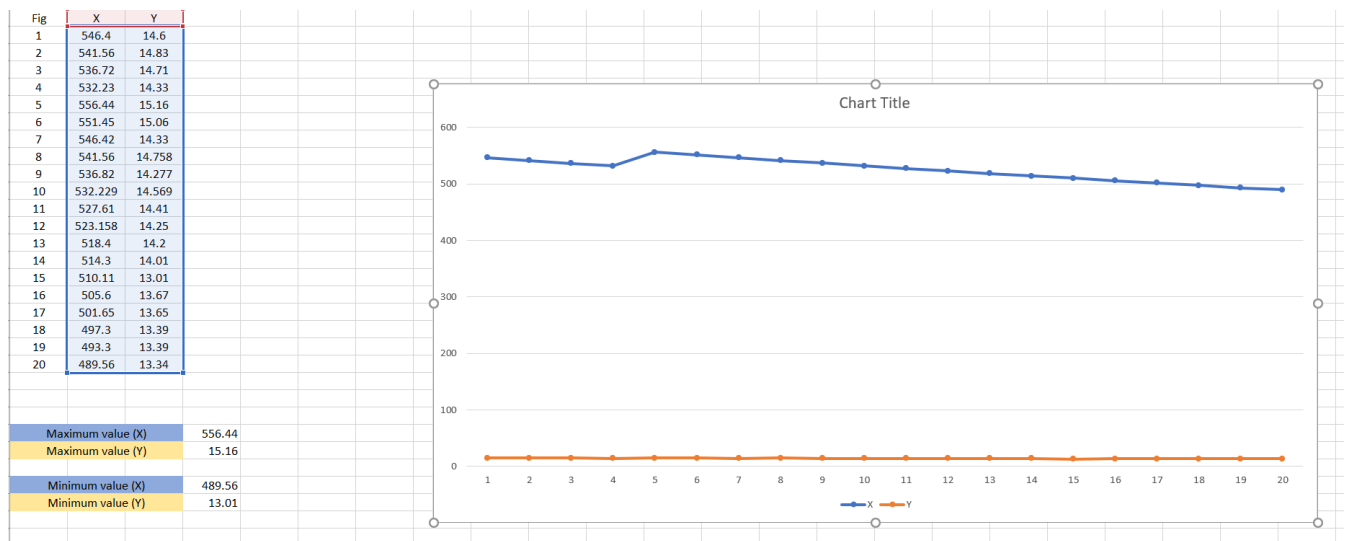


Fig :- Comparison for lift and drag coefficients of HGV model

CHAPTER 8

RESULT AND DISCUSSION

As a result of plotting the graphs, the pareto optimal solution is obtained in the form of graphs and the trajectory optimization is carried out using the matlab optimization tool based on the given constraints and variables. The experimental values are then compared with the simulations and are found to be almost accurate and precise. The 5 different constraint values were run in matlab code to obtain 30 different iterations which were then plotted in graph to compare lift and drag coefficients respectively.

CHAPTER 9

CONCLUSION

The project is carried out successfully starting from matlab simulation to design and fabrication and lastly testing. The HGV design is mainly done in Solidworks Educational Software taking inspiration from other prototype models under development. The matlab simulation is then carried out taking into consideration the heating rate constraint and using the GA solver in Matlab thus comparing the values of Drag, Lift with respect to the altitude. The fabrication part was done in a 3D printer and was assembled later. The model then was tested successfully inside a wind tunnel to calculate the lift and drag values at an higher angle of attack . The experimental values were then compared with theoretical values and found out to be almost the same and thus the trajectory optimization of the hypersonic glider vehicle was successfully carried out.

CHAPTER 10

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