

MULTIDISCIPLINARY OPTIMIZATION IN AEROSPACE DESIGN: THE EMERGING TECHNOLOGY FOR COMPLEX SYSTEMS

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Abstract

The design, development and launching of a space vehicle is a highly interdisciplinary activity, with strong interaction between aerodynamics, structures, thermodynamics, flight mechanics, navigation-guidance-control, propulsion, telemetry, range safety etc. Performance, weight and finally cost optimality are most important in these systems. The desired goals are best achieved through formal disciplinary and multi-disciplinary optimization. In the context of the Indian space vehicle design, optimization of trajectories is routinely carried out for all missions. In recent times a number of aerodynamic shape optimization problems are taken up, many of them using high fidelity CFD codes. The need to limit the launch cost drives the increasing use of multi-level and multidisciplinary design optimization. This paper discusses the class of optimization algorithms used and developed along with a few case studies on disciplinary and multi-level optimization in the trajectory design of orbital and interplanetary missions, and emphasizes the emerging trends in the multidisciplinary design optimization of aerospace systems.

Introduction

The progress in optimization methods in the last 50 years has been enormous. It is indeed true that the foundations for these developments really lie in the contributions of mathematical giants like Cauchy, Euler, Gauss, Lagrange, Newton, Pontryagin and other masters of such caliber. But many new and innovative ideas have been introduced in recent times. For continuously differentiable functions, a number of variable metric methods have been proposed; their mathematical properties of convergence well-established; and consistent and successful practical application has been demonstrated. The strides made in the use of random search and related methods have brought in many possibilities in the realm of global optimization and also in cases, where derivatives are difficult to calculate, or even do not exist. Several of these successful methods mimic natural processes, for example, the natural selection and the evolutionary principles embedded in the genetic algorithms for optimization. With such developments in the recent past, the present day designer has a spectrum of techniques on hand. One also now has the task of choosing appropriate methods depending on the complexity of the design task. There is also a need to innovate over the existing methods, since, thankfully, there is no best method or suite of methods that exists; and there is always a new problem that may require a departure from the beaten track.

There is a substantial amount of application-oriented research in the field of aerospace dynamics. The high investments needed for space programmes demand that maximum returns are extracted from the system. At the same time the enormous impact of a failed space mission, in terms of cost, schedule and accountability, necessarily requires that the design must also be robust. Trajectory optimization is routinely done for every space launch, and the methods are being continuously improved as more and more complex mission scenarios and constraints are considered. Optimal guidance laws catering to diverse applications are generated. Aerodynamic shape optimization is a classical topic with reference drag minimization. But multiple regimes of flight and more accurate flow simulation models necessitate constant improvement of the design techniques. This is also true in the structures, propulsion and thermal design areas of aerospace. Lunar and planetary mission studies offer the designer a challenging area for optimization. While all the pre-1980 lunar missions take the conventional route of lunar transfer from low-Earth parking orbits, recent optimal mission designs open up new avenues for lunar and planetary programmes. The aim of this paper is to present a few typical applications of the methods of optimization in aerospace; and identify the future directions in this very important area.

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Trajectory optimization plays a vital role in the design of a launch vehicle, starting from initial vehicle sizing and definition phase to launch-day operations of steering programme selection. The paper starts with a discussion on the developments in this area.

We further discuss the realm of lunar gravity assist trajectories to reach geo-stationary orbits (GSO). It may look paradoxical, but it is true that under certain conditions, we can reach GSO more cost effectively by going via the Moon. This is demonstrated in this study by the application of genetic algorithms. One can also reach several other interesting orbits via the Moon, for example a circular Earth orbit of the size of lunar orbit itself, without the need of any additional propulsive force. This section also presents interesting modifications in the genetic algorithm that improve the quality of convergence.

Aerodynamic shape optimization is an area where concerted efforts will be made in the coming years. We introduce the problem, and present two example of typical shape optimization. First is an example of the use of genetic algorithm in the design of a Mach 12 contoured nozzle. Here, an efficient Navier-Stokes CFD code PARAS (Parallel Aerodynamic Simulator) has been used in the optimization to account for the viscous effects in the nozzle design. The second example presents an optimization of inviscid scramjet air intake. The results are presented in the form of Pareto optimal sets for two, three or four ramps and single cowl configurations. It is observed that the optimization process significantly improves the performance, and for the same length of the air-intake, the pressure recovery is significantly increased. The Pareto optimal front gives the designer a range of choice among optimal solutions to make an informed decision.

Finally we discuss the future directions both in the development of optimization methods and their aerospace applications. The main issues here are approaches for integrated system design, multi-disciplinary problems, and multi-objective optimization. Random search methods provide a great promise, but solutions are to be found to the problem of large number of function evaluations needed in these methods. Hybrid algorithms and parallel thinking algorithms can be very attractive. Applications to complex hypersonic aerodynamic vehicle design, interplanetary travel are some of the application challenges.

Through the examples discussed here, we focus on the gainful applications of classical and modern optimization methods to a number of very interesting problems in space

dynamics. There are innumerable numbers of such applications in many other important areas of space technology, for example, propulsion, structural optimization, and integrated vehicle design. The future trends, in the areas of algorithmic research and also practical applications, are discussed.

Trajectory Optimization

Trajectory optimization plays a vital role in the design of aerospace mission. The emphasis on low cost access to space has inspired many recent developments in the methodology of trajectory optimization. Trajectory optimization with detailed launch vehicle and mission constraints is a challenging non-linear problem. The task is further made complex when different phases of the trajectory have different objectives of optimization and also different path constraints. Efforts to solve this effectively using the state of the art techniques are being continuously made. In this section, we describe the salient features of the software package PYOPT developed and validated at the Indian Space Research Organization employing the concepts of diagonalized multiplier methods for constrained pitch and yaw trajectory optimization.

In this algorithm, there is only a single multi-level sequence of state and multiplier updates using an augmented Lagrangian. Han and Tapia multiplier updates are used due to their special role in diagonalized multiplier methods (DMM), being the only single update procedure with quadratic convergence. Like the recursive quadratic programming (RQP), DMM is a single sequence minimization technique for non-linear programming and avoids the sequence of minimization problems inherent in classical augmented Lagrangian methods. It is found that performance of DMM is better in several case studies compared to classical methods and comparable to that of RQP. Violent initial multiplier updates are avoided by minimizing the Kuhn-Tucker vector norm along the Han-Tapia multiplier update directions. The system dynamics facilitates routine and operational design and analysis.

Mathematical Modeling

Let a vector s denote the state of the dynamical system (launch vehicle in motion) and the dynamics of this system depend on vector u of the control variables that are parameterized and could be specified. The system dynamics could be represented by

$$\frac{ds}{dt} = F(s, u, t), \quad t_0 \leq t \leq t_f \quad (1)$$

Our interest is to maximize a performance index (payload, velocity etc.,) that depends on $s(t_f)$. Since this depends on the choice of \mathbf{u} through the dynamical equations of the system, performance index also depends on \mathbf{u} . The task is to select the control vector \mathbf{u} , such that the cost function is maximized while satisfying various specified state and path constraints.

To solve this problem, the designer must be equipped with (i) a capability to simulate the system dynamics (ii) a procedure to ensure constraint satisfaction and (iii) a method to vary the control vector so as to optimize the objective function. Some of the constraints are carefully modelled in the system dynamics itself, in order to make a highly constrained problem, a less constrained one. It is also assumed that the decision variables are parameterized, so that the problem is to find a finite number of control parameters for each system instead of a continuous function. With this parametrization, the performance index becomes a function of a finite number of control parameters for each system. The optimization of this function is done using the methods of constrained non-linear optimization. The details of the dynamical equations and the algorithm are given in Adimurthy [1].

Description of PYOPT

The process of steering programme design using PYOPT is depicted in Fig. 1. The program PYOPT can be used to optimize the payload of a satellite launch vehicle under various specified constraints. Some of the major constraints are the following:

- Vertical rise time selected to clear launcher and then pitch down maneuver starts
- Gravity turn starts at appropriate Q_α values to maximize the payload
- Wind biasing to reduce loads during atmospheric regime
- Stage separation dynamic pressure should be sufficiently small
- Stage Impact point constraints to be satisfied
- Instantaneous Impact Point (IIP) constraints to be satisfied
- Heat shield separation altitude should satisfy required thermal constraints
- Trajectory Dipping Constraints of any low thrust stage to be satisfied

- Support orbit size constraints
- Tracking stations and visibility related constraints
- Perigee altitude, Apogee altitude, and argument of perigee constraints to be satisfied.

Multi-System Optimization

Any complex aerospace design problem involves the design of a system of systems, representing multiple disciplines. One of the ways adopted to solve such a problem is to decompose the main problem into various sub systems. Similar concept can also be utilized to address the design of a launch vehicle trajectory with many state and path constraints. Some trajectories have a flat segment for a considerably longer duration during upper stage flight with low acceleration and is very sensitive to the changes in the design variables. Betts [2], in his excellent survey of numerical methods for trajectory optimization, emphasizes the sensitivity of non-linear constraints to changes in the variables in the initial and middle portions of the trajectory making the problem very difficult to solve. Gath and Calise [3] describe a hybrid analytical/numerical approach, wherein initially analytical vacuum solution is used and atmospheric effects are gradually introduced until a converged solution is obtained. Flight path designs for vehicle having upper stages with low thrust to weight ratio are discussed. In these trajectories, dipping of the altitude is observed which may have serious thermal implications for the spacecraft. They note that it is difficult to get converged solutions for low thrust/weight ratio upper stages. This is further complicated by the fact that different phases of the flight path have different objective criteria and path constraints. Multi system algorithms can effectively handle such problems. Here we present the extension of the DMM to multi-level problems as described in Adimurthy, Tandon, Ravikumar and Jessy Antony [4].

Many engineering applications require optimal design of the system, wherein the original system comprises many sub systems. Launch vehicle trajectory is one such application in aerospace engineering. The problem of trajectory optimization with different objective criteria, path and state constraints for different segments of the trajectory can be effectively addressed by multi-level optimization. There exist different topologies for defining the systems and their inter-connectivity. A multi-level optimization algorithm can be employed in which the repeated local sub system optimizations are not necessary.

There will be a single, multi-level sequence of updates for state and multipliers in the framework of an augmented Lagrangian.

Results for Two-System Optimization

The robustness of the solutions generated by the proposed algorithm is demonstrated through running the code for multi-system trajectory optimization for a number of cases with wildly varying initial guess points. Any complex aerospace design problem involves the design of a system of systems, representing multiple disciplines. One of the topologies adopted to solve such a problem usually decomposes the main problem into various sub systems. In the present case the design of a launch vehicle trajectory with many state and path constraints is considered. This flight path has a flat segment for a considerably longer duration during upper stage flight with low acceleration and is very sensitive to the changes in the design variables. The problem is handled by multi system algorithm with two systems, each with specified constraints. The problem is decomposed into two segments. One segment deals with the ascent trajectory and payload optimization and the second one handles the impact trajectory. The dipping constraint is handled in the exo-atmospheric payload optimization branch while the impact trajectory branch handles the constraint on fall zone and atmospheric load constraints. In this typical example the first system is taken with five control parameters and constraints on perigee, apogee and flight path angle at maximum dip altitude. The second system is taken with three design variables with a constraint on the spent stage impact point. The objective criterion for the first system was payload and that for the second system was semi-major axis of the reentry trajectory at stage burnout. In this example the launch vehicle considered has a long burning low thrust to weight to ratio upper stage. During this flight regime unconstrained optimal trajectories will dip alarmingly which are not acceptable from the considerations of heat load to the spacecraft. For this reason, this trajectory is extremely sensitive to changes in the control parameters, especially those connected with the initial phase of the trajectory. This constraint ensures that the trajectory is flat for a long duration but does not dip.

Gradient Change Measure

In order to reduce the cost and time of computing gradients, a gradient change measure is proposed. This measure is an integral measure of the change in the function gradients and constraint gradients to be used to deter-

mine the frequency of the gradient calculation. This approach is expected to reduce substantially the run time for large engineering optimizations. Let the gradients of the objective function during the previous iteration and during the current iteration be FP_i and FC_i respectively, with $i = 1, \dots, n$ where n is number of control variables. Let the gradients of the constraints during the previous iteration and during the current iteration be HP_j and HC_j respectively, with $j = 1, \dots, m$ where m is number of constraints.

$$\text{Let } X = \sum_{i=1,n} FP_i * FC_i + \sum_{j=1,m} \sum_{i=1,n} HP_{j,i} * HC_{j,i},$$

$$\text{and } Y = \sum_{i=1,n} FC_i * FC_i + \sum_{j=1,m} \sum_{i=1,n} HC_{j,i} * HC_{j,i}. \quad (2)$$

Then the proposed integral change measure is given by $(X-Y)/X$.

The initial guess points are given such that initial orbits and constraints very wild to the extent that some are sub-orbital. A summary of the initial and converged values of orbits and constraints are given in Table-1. In all the cases the solution points are the same, the system converged to a payload of 4850 ± 5 kg with all the constraints very closely satisfied. The initial guesses used are away from the optimum. Constraints on fall zones are easily handled in this two-level system approach, which will be very useful while designing trajectory for a fresh vehicle with totally different characteristics. The constraint on dipping of trajectory is also perfectly satisfied in all the cases, for low thrust to weight ratio upper stages although some difficulty is reported in the literature, for example in Gath and Calise [3]

Optimization in Lunar and Interplanetary Missions

Targeting the Moon

Trajectory design and carrying out maneuvers to achieve the desired lunar trajectory minimizing the fuel requirement is an important aspect of mission planning. During its travel, lunar spacecraft is essentially subjected to the gravity fields of the Earth and the Moon. To generate the transfer trajectory characteristics for translunar injection (TLI), a three-body problem is to be solved for which there is no known closed-form solution. Many approximate techniques and algorithms exist to generate the lunar transfer trajectory characteristics. They are based on point conic, patched conic or pseudo conic techniques and they provide quick data for preliminary mission design and

analysis. Achieving a specified lunar parking orbit altitude and inclination accurately is the key to the success of a lunar mission. The translunar injection conditions/Earth parking orbit characteristics are to be chosen such that the resulting trajectory will end up with specified target conditions. In reality, the lunarcraft will undergo perturbations due to non-spherical gravity fields of the bodies. The transfer trajectory will deviate from its expected path and fail to achieve the target accurately, if these perturbations are not considered in the trajectory determination process. Mainly, the asphericity of the Earth causes these devia-

tions in the neighborhood of the Earth. The only known way to find the precise translunar injection characteristics accounting these perturbations is by search and by numerically simulating the trajectories. Genetic algorithm is used to regulate the search and to find such a precision trajectory design. Table-2 provides comparative results of the trajectory obtained using Genetic algorithm with an analytical technique. The errors in achieving the target parameters with the analytical technique may be noted.

Table-1 : Convergence study of two-system optimization

Case	Initial Values				Converged Values			
	Apogee (km)	Perigee (km)	Stage Impact (deg)	Dip angle (deg)	apogee (km)	Perigee (km)	Stage Impact (deg)	Dip Angle (deg)
1	16378.0	437.5	89.79	89.94	35915.8	181.2	86.49	89.99
2	20537.8	388.6	89.39	89.29	35975.1	180.7	86.49	89.98
3	26643.0	290.0	88.24	88.69	36048.0	180.6	86.51	89.99
4	32859.9	189.2	86.78	89.83	35965.2	179.9	86.50	89.98
5	39441.4	60.2	84.85	91.31	35990.1	180.2	86.51	89.97
6	47347.8	-44.8	83.01	92.54	36000.1	180.6	86.50	89.98
7	46846.0	-192.3	80.80	94.00	36008.3	180.3	86.51	89.99
8	283.4	-3091.0	88.22	103.2	35976.1	180.2	86.50	89.98

Table-2 : Comparison of transfer trajectory characteristics of biased non-impact algorithm and genetic algorithm

	Initial conditions of transfer trajectory (earth centered)		Achieved hyperbolic approach trajectory (moon centered)	
	Using biased non-impact algorithm	Using genetic algorithm	Biased non-impact algorithm	Genetic algorithm
a, km	200137.656	206171.3364	07824.174	-7695.922
e	0.96663	0.96761	2.0142	1.3557
i, deg	18.0	18.0	25.483	90.000
ω , deg	168.6142	168.5031	132.226	142.5924
Ω , deg	352.6493	352.7066	62.059	76.8179
Periselinum alt., km	-	-	6196.98	1000.20

1. The biased non-impact algorithm model is limited to spherical gravity fields of the Earth, the moon and the Sun
2. The precision trajectory of GA includes Earth's J_2 effect also
3. Achieved hyperbolic approach trajectory parameters are with full force model

Optimal Transfer to GSO Using Lunar Gravity Assist

The geo-stationary satellites have become integral part of human life. They help to improve the social and economical status of the mankind. The launch of this class of satellites is inevitable to cater to the needs of future expansions in communications and telecasting and as a replacement to the existing ones. With the heavy increase in the demand of such satellites, making these launches economical is very essential. Towards this goal, many unconventional scenarios of transfers are being discussed among the scientific community.

Conventionally, the transfer to geo-stationary orbit (GSO) is achieved by placing the spacecraft in a geo-stationary transfer orbit (GTO), which is a highly elliptic orbit, with perigee around 200 km and apogee around 36000 km. Normally because of launch station limitations, the GTO orbital plane is inclined to the Earth equatorial plane. Large amount of propellant is to be spent to effect the plane change to attain zero inclination as well as to raise the perigee to 36000 km. These manoeuvres make the mission cost high. Hence, alternate approaches using the lunar gravity field for these maneuvers are discussed in the literature.

The approach trajectory to Moon, when it goes through lunar gravity field, undergoes a change of the plane of motion and also gains or loses energy relative to Earth during encounter with Moon. After the close approach, the speed of the space vehicle relative to Earth can either increase or decrease depending on the geometry of the approach trajectory relative to the Moon. The direction of motion also changes because of lunar gravity. The post encounter trajectory can have a wide spectrum of orbital characteristics. It can be an escape trajectory from the Earth's gravity field; it can be an elliptic orbit, with very high perigee altitudes of the order of several hundred thousand kilometers; the inclinations of these orbits also can be drastically different from the incoming orbit. This phenomenon can be judiciously used to raise the perigee of the approach trajectory, rotate the apsidal line and change the orbital inclination by choosing appropriate initial transfer orbit characteristics. This mission design concept is found to be reducing the launch cost for high inclination orbits. The transfer of spacecraft to geostationary orbit from a low earth parking orbit involves identification of appropriate transfer trajectory characteristics resulting in a low inclination and GSO altitude after encounter with Moon. The problem of identification of the

appropriate transfer trajectory characteristics is solved as a parametric optimization problem using genetic algorithm. It is found that the performance of the regular genetic algorithm is not satisfactory in view of the extreme sensitivity of the out-going trajectory to initial conditions. To obtain good convergence a new modification of (GA) with adaptive bounds (GAAB) is implemented, which provided excellent results.

Transfer Trajectory Design

There are several techniques to design the transfer trajectories of one way travel. They can be grouped into three main categories (i) point / patched conic method (ii) Pseudostate theory based methods (iii) search by numerical integration. In the point conic method, the transfer trajectory is obtained ignoring the presence of lunar gravity field and the patched conic method considers both the gravity fields of Earth and Moon but only one of them at a given time. Recently an integrated algorithm has been developed by Ramanan [5] based on pseudostate technique. This technique includes both the gravity fields simultaneously in the transfer trajectory design process but by assuming that the individual terms in the three-body equations of motion can be integrated independently using two-body conic solutions. These techniques generate analytical approximate solution of a 3-body problem (Earth, Moon, Spacecraft) under different assumptions on the forces acting on the spacecraft to simplify the problem into a two-body problem, as there is no known closed form solution to a 3-body problem. The approximate closed form solutions of transfer trajectory characteristics result in errors in achieving the target constraints, under realistic force models. The errors in one-way transfers can be easily handled. However, in two-way transfers involving gravity assist, with in-coming and out-going trajectories, the initial errors have a predominant effect on the out-going trajectories. Therefore, the only accurate method to design such transfer trajectories is a numerical one.

The design of the lunar gravity assist trajectory to GSO from low earth parking orbit by search by numerical integration is the only way in the absence of other efficient algorithms. In this technique, the complete trajectory, starting from the parking orbit after trans lunar injection and ending on reaching the GSO altitude and inclination after Moon encounter, is generated for several sets of trajectory characteristics. This trajectory is divided into three phases (i) approach trajectory phase towards Moon (ii) gravity assist phase around Moon (iii) return trajectory phase towards Earth after Moon encounter.

Results Using Genetic Algorithm With Adaptive Bounds

The performance of GAAB with the regular GA is compared in Fig.2. Clearly GAAB outperforms the regular GA. If one considers an initial transfer orbit of 300x36000 at an inclination of 50 deg, going to GSO by conventional route would require a velocity addition of 2,350 m/s. But using lunar gravity assist, the total velocity requirement would be only 1,766 m/s resulting in a gain of 585 m/s. Typical design of the optimal trajectory is depicted in Fig.3.

Lunar Gravity Assist to Achieve Circular Post-Encounter Orbits

To bring out the benefits of lunar gravity assist, another illustration is presented here. With appropriately chosen initial transfer orbit that is highly elliptic with a 300 km perigee, it is demonstrated that a circular orbit of 360,000 km (nearly the distance of Moon from the Earth) could be achieved after encounter with Moon. For this, we minimize the eccentricity of the post-encounter orbit. The initial transfer conditions required for this, and the parameters of the outgoing orbit after lunar encounter are given in the Table-3.

Even though the out going orbit may not have any practical significance, this exercise demonstrates that the genetic algorithm can be used effectively to get such a circular orbit. The out going eccentricity is minimized to 0.00809, from an incoming value of 0.96515, solely by lunar interaction. It may be noted that the outgoing inclination has increased to nearly 80 deg. In this case, the velocity gain due to lunar encounter works out to be 868 m/s.

Similar applications of GA are made in the area of space debris management. The problem of space debris is

a recent phenomenon, and is an outcome of man’s space exploration. These unwanted objects cause risk to operational satellites. Re-entry of large debris is always of concern, and precise estimations of the reentry time and location are difficult to make. Analysis of the terminal phase of such decay using optimization methods can improve the predictive ability. An application of genetic algorithm in such problems is presented by Sharma, Bandyopadhyay, and Adimurthy [6].

Aerodynamic Shape Optimization

During the design of any Aerodynamic configuration, one has to cater to various requirements and often these are contradictory in nature. It calls for a design optimization of the configuration, which satisfies various requirements. Earlier, this kind of optimization has been carried out mostly by judgement of the designer based on his experience and understanding of the aerodynamic behaviour of the configuration and it was not generally a rigorous optimization. Only recently, rigorous attempts on the aerodynamic shape optimisation have been reported. For example, Sung and Kwon [7] have used a gradient-based optimization, an adjoint method for finding sensitivities for the problem of drag minimization of an airfoil with a Navier-Stokes formulation for flow analysis. Holst and Pulliam [8] have used a real coded genetic algorithm for aerodynamic shape optimization. Adimurthy, Selent, Rudolph and Weigand [9] have used genetic algorithms for the shape optimization of cooling channels for optimum cooling of bodies by internal convection. Further in this paper, additional convergence accelerations have been obtained by combining genetic algorithms with gradient-based variable metric algorithms. Studies like these are now made possible with the advent of large computing power available and also development of new algorithms for computation of flow and the performance index evaluation.

Table-3 : Transfer to a nearly circular orbit using lunar gravity assist

	Incoming orbit	Outgoing orbit
Time of Departure	18-01-2007 06:27:27	-----
Perigee Altitude	300 km	359696 km
Apogee Altitude	370147.45 km	366443 km
Eccentricity	0.96515	0.00809
Inclination	50 deg	79.8 deg
Encounter Time	-----	23-01-2007 17:20:00

Optimization of Mach 12 Contour Nozzle Design Including Viscous Effects

In this section an example of the use of genetic algorithm in the design of a Mach 12 contoured nozzle is presented. The aim is to produce a uniform Mach number over a specified region in the nozzle exit plane and to limit the flow angularity at the exit plane, over the same region, within a given limit. As hypersonic wind tunnel nozzles with Mach numbers greater than 8 are dominated with strong viscous effects, the nozzle contour generated by the conventional Method-of-Characteristics does not meet the design requirements when boundary layer corrections are made [10].

In the present work, the Parallel Aerodynamic Simulator Code (PARAS) that uses surface oriented mesh system has been used to simulate the flow inside the axisymmetric nozzle [11]. The code solves Navier-Stokes equations using a finite-volume approach and is very robust and fast. The optimization tool used is the Genetic algorithm driver GA170 [12], which has been interfaced with PARAS code. CFD solutions are used to evaluate the objective function in each function evaluation of the GA process. To represent the nozzle contour (Fig.4) in terms of certain parameter vector \mathbf{P} ($p_1, p_2, p_3, \dots, p_n$), the nozzle contour is divided into 5 segments and is represented as follows:

For

$$\begin{aligned} 0 \leq x \leq x_1 & \quad r = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \\ x_1 \leq x \leq x_2 & \quad r = a_4 + a_5 x + a_6 x^2 + a_7 x^3 \\ x_2 \leq x \leq x_3 & \quad r = a_8 + a_9 x + a_{10} x^2 + a_{11} x^3 \\ x_3 \leq x \leq x_4 & \quad r = a_{12} + a_{13} x + a_{14} x^2 + a_{15} x^3 \\ x_4 \leq x \leq x_5 & \quad r = a_{16} + a_{17} x + a_{18} x^2 + a_{19} x^3 \end{aligned} \quad (3)$$

The above five cubic splines result in 20 coefficients ($a_0 \dots a_{19}$) assuming that the locations $x_1 \dots x_5$ are known. The slopes at the nozzle throat and exit planes are assumed to zero. The continuity of radius, slope and curvature at the four interfaces give rise to 12 conditions. The nozzle exit radius is specified. The radius at the interfaces gives 4 conditions. With these 20 conditions, the above set of linear simultaneous equations is solved using Gauss-Siedel method. After getting the coefficients, ($a_0 \dots a_{19}$), the nozzle contour can be determined [13]. The length of the nozzle is also kept as a floating parameter. A constant inlet Mach number of unity has been taken and the tunnel operating conditions have been taken as $p_0 = 68$

KSC, $T_0 = 1500$ K and ratio of specific heats $\gamma = 1.311$. Besides the radii r_{th}, r_1, r_2, r_3 and r_4 , the length of the nozzle 'L' (x_5) is also considered as a parameter. The nozzle exit radius is 0.5m, which is the test section radius, and is fixed. The nominal values of these parameters are arrived at using the MOC contour with boundary layer correction.

The objective function consists of two parts. First part, takes into account the deviation of actual Mach number M_{act} from the target Mach number M_{tar} (=12) and the second part the deviation of flow angularity α_{act} from the target flow angularity α_{tar} (0.2 deg). These are evaluated in the core of the nozzle exit. Thus, we have,

$$Obj(P) = -1/N \left[\phi_M \sum (M_{act} - M_{tar})^2 + \phi_\alpha \sum (\alpha_{act} - \alpha_{tar})^2 \right] \quad (4)$$

where ' \mathbf{P} ' is the parameter vector and ' N ' is the number grid cells in the core of the nozzle exit. Values of ϕ_M and ϕ_α are taken as 0.7 and 0.3 respectively, which are weighting factors.

Figure 5 shows the objective function as defined above with number of generations. It is seen that the objective function falls by 30% in about 68 generations. Figs. 6 and 7 show the radial Mach number and flow angularity distribution at different generations. It is seen that the GA driver changes the parameters toward the goal set in terms of both Mach number and flow angularity over one half the radius at the nozzle exit plane. All the above computations have been carried out on the Parallel TFLOPS cluster and typically each CFD solution takes 3 min for 20000 iterations. The present results have been generated with lesser number of population and lesser number of generations. But they indicate the correct trends in obtaining the optimum solution by combining the standard genetic algorithm tools with a sophisticated CFD tool. Bigger population size and greater number of generations will likely to yield the final design contour satisfying the design specifications.

Optimisation of an Inviscid Scramjet Air-Intake

A scramjet engine based system becomes a candidate choice for low cost access to space due to significantly higher specific impulse compared to rocket-based propulsion systems. Thus, scramjet propulsion is being explored extensively around the world. The integrated air-breathing system involves the following three major sub-systems:

1. A hypersonic air-intake / fore body
2. Scramjet combustor module
3. Body integrated nozzle module.

All of the above pose interesting research and development challenges in the area of aerodynamics. As the thrust obtained from such vehicles is usually smaller than that of the conventional solid and liquid propellant rocket systems, the parent vehicles and the propulsion modules have to be designed very carefully in order to maximize the net thrust (thrust minus drag) and to minimize the weight. For this, each sub-system needs to be optimized to deliver its maximum and the total system too needs to be optimized for best performance.

The aim of the exercise presented here is to optimize a 2-D inviscid air intake configuration for defined entry and exit conditions and obtain:

- Maximum pressure recovery (to maximize the thrust of the engine)
- Minimum length (to minimize air-intake weight)
- Ensure shock on lip condition (to maximize mass flow and keep the flow uniform inside the air-intake)

The typical intake design optimization studies have been carried out for Free stream Mach Number of 6.5, intake exit Mach Number of 2.43 and cowl lip height of 0.4971 m and described in detail in Pankaj Priyadarshi et al. [14].

Intake Configuration and the Optimization Problem

In general a supersonic air-intake consists of multiple ramp and cowl surfaces to compress the free stream to low enough Mach numbers. A mixed compression supersonic/hypersonic air-intake can be parameterized as shown in Fig.8. δ_i are the flow turning angles for intake ramps with respect to the local incoming flow. For cowl, it is the flow turning angle with respect to V_∞ . β_i are the corresponding shock angles. These are required for satisfying shock on lip constraints. The design parameters for the problem are the ramp angles δ_i . They are bounded between 0° and 30° .

The following Design objectives were considered:

- Maximize total pressure recovery
- Minimize total length of intake ($l_1 + l_{n+m}$)

Three different optimization codes are employed in this study and are described in [14]. While the NSGA II code [15] optimizes both the objectives together, GAABCONS and DAKOTA [16] optimize the pressure recovery with air intake length as a constraint. The following constraints are considered:

- Exit Mach number after the ramps and cowl shock should be 2.43. This is a non-linear equality constraint.
- Length of the air-intake was taken as a constraint for GAABCONS and DAKOTA codes, both of which are single objective optimization codes. By taking various intake lengths as constraints, the Pareto-optimal front can be constructed. This too is a non-linear equality constraint.

The optimization algorithm requires total pressure recovery and air-intake length, corresponding to the input set of ramp and cowl angles, from the aerodynamics module. For computation of pressure recovery it is essential to compute the properties behind the shocks originating from the ramps and the cowl. Oblique shock relations have been used to compute the properties behind the respective shocks.

The condition that the shocks originating from various ramps focus at the cowl lip forms a set of 'n' stiff non-linear equality constraints for the optimization problem. To overcome this and to reduce the number of design parameters (length of each ramp) the ramps have been kept floating (i.e., it can be placed at any required location axially). First the shock angles corresponding to the set of ramp and cowl angles are computed. Now, the ramps are so placed that the shocks focus at the cowl lip. This fixes the location and length of all ramps. The length of the final ramp is fixed by the location of impingement of the cowl shock. The subsequent surface is made parallel to the cowl surface thereby avoiding any further shock reflection. It also helps in avoiding separation due to adverse pressure gradient at the cowl shock impingement location.

Results and Discussion

Inviscid intake design optimization studies are carried out for combination of multiple ramp and cowl surfaces. For two and more ramp cases rigorous optimization studies, as described above, have been carried out where the objective is to maximize the total pressure recovery and minimize the total length of the air-intake. The results of the study are shown in Fig. 9 in the form of Pareto-optimal

fronts for the various numbers of ramps of the air-intake. Using this information, the designer can make useful decisions for implementation. For example, for four ramps and one cowl system maximum inviscid pressure recovery that can be achieved is $\approx 67\%$ with intake length of 2.2m. For 1.8 m length, the pressure recovery is $\approx 64\%$.

There exists a region in the Pareto-optimal design space where increase in pressure recovery is almost linear with the increase in air-intake length. On the other hand, at peak pressure recovery, the air intake length is very sensitive to change in pressure recovery. This gives the designer a choice among the optimal solutions for finalizing the intake configuration. Three ramps and one cowl system is taken up for verification of the Pareto-optimal front generated using NSGA II. For this, GAABCONS and DAKOTA are employed. Fig. 10 shows the comparison. It can be seen that the Pareto-optimal fronts obtained using all the three codes match quite well.

The solutions presented here are inviscid solutions. It may however be noted that viscous effects play an important role in the design of the intake and similar design exercise must be done taking into account the viscous equations.

Future Optimization Algorithms and Applications

In this paper, we attempted to present a glimpse of optimization applications in the broad area of aerospace dynamics. It aims at providing a flavor of the spectrum of methods and applications that can be envisaged in this field.

In this concluding section, we present a discussion on the promising future directions in optimization algorithms and applications. Optimization methods based on stochastic approach, and in particular, evolutionary algorithms, are extensively being used in aeronautics. Despite their advantages, population based search algorithms require excessive computer time due to large number of candidate solutions, which need to be evaluated. Efforts are on in making stochastic optimization both efficient and effective. A large number of researchers are working in the area of reducing costly objective function evaluation time by use of surrogate or approximate models. The need for future research in developing a comprehensive approach to help reduce the required data size for optimization is emphasized.

There are very good reasons for the popularity and widespread use of genetic algorithms; that they are robust; they obtain global optimum; can easily handle multi-objective optimization; can be easily used in parallel computing environment; they can handle a mix of discrete, integer and continuous design variables; and that they can be easily integrated with domain knowledge codes. On the other hand the main drawback of GA is the high number of function evaluations. One of the methods to reduce the cost is adaptation. Adaptation of the parameters and operators involved in the evolutionary algorithms is a promising area of research. The concept here is that evolution can be used not only for finding the solution to the problem, but also for modifying the algorithm itself. This self-adaptation strategy helps overcoming any need for manual tuning of the parameters. One such new method, which has substantially improved the quality of the solutions, is the genetic algorithm with adaptive bounds (GAAB), which we used in some of the examples presented here.

Since the new computing systems derive the computational speed through parallel processing, optimization methods that have roots in serial thinking can be poor methods for use on such systems. Specific goals for future research are in the use of evolutionary algorithms to large-scale design problems through more efficient implementation in a parallel computing environment. Prominent scientific areas in aerospace, which are benefited by the parallel computing technology, are fluid mechanics, aerodynamics, thermal analysis, structures, and atmospheric sciences. Computational Fluid Dynamics (CFD) is the most typical example where 3-D calculations are now affordable for real life aerospace problems, even though there are still open questions in several specific areas like turbulence modeling, transition and chemical interactions. Optimization problems in the aeronautics are among the most complex ones in engineering. They are multi-objective and multi-disciplinary, involving competitive disciplines, which cannot be handled in isolation. A practical way to handle such complex design problems is multi-level approach. One can attribute two distinct meanings to the multi-level approach in the context of multi-disciplinary design. One relates to the process of design in which a preliminary design is first done followed by a detailed component design. The other relates to the algorithmic approach of decomposition of the complex design to a number of levels, and solving the broad design problem in an iterative fashion. There is a need for continued research in the development of multi-level algorithms followed by application to real multi-disciplinary design involving

aero, thermal, structural, propulsion, and mission subsystems.

With renewed interest in lunar and interplanetary programmes, increased use of optimization in these complex missions is foreseen. The interplanetary trajectories are very sensitive to small variations in the initial conditions. Hence the methods used should be very robust, and the mathematical models very accurate. Minimizing the energy requirements to such missions by a clever use of multiple planetary swing-bys is one very interesting application. Using passive systems such as solar sails, one can substantially reduce the propulsive requirements for interplanetary missions

Aerodynamic shape optimization is an area, which is going to attract considerable attention in the coming years. It is evident that CFD plays a crucial role in aerodynamic shape optimization. Through CFD tools the aerodynamic performance of complex shapes can be evaluated without resorting to costly wind tunnel experiments. In this kind of problems, the role of shape parameterization is very important. Various parameterization methods for airfoils and wings are available in literature. However, for more complex shapes of future aerospace vehicles further study is needed for effective parameterization. Currently, the technology of shape optimization is essentially limited to Euler-level aerodynamic computations. Even though some Navier-Stokes designs are available, concerted efforts and further research is needed in handling the complex aero thermal shape optimization in the framework of viscous models. Adjoint-based methods are attractive in reducing the cost of gradient evaluations. Another aspect that needs attention is that the aerodynamic configuration needs to perform optimally at more than one flight regime, for example, re-entry and landing.

A promising area of research is the development of hybrid algorithms. This approach is attractive because, different algorithms perform successfully in different regimes of an optimization process. For example, evolutionary searches are very good in identifying clusters of good design options, but are poor in local convergence. Variable metric methods, on the other hand, have quadratic convergence properties near the local optima. The good features of both the methods can be integrated in a hybrid algorithm. The successful application of such hybrid algorithms should be demonstrated for complex practical problems.

The emphasis for the future will be in the multidisciplinary design optimization (MDO). New algorithmic topologies for MDO are under study; and the individual domain codes are being improved for MDO application. In this environment of integrated optimization, more and more problems with multiple objectives will be posed. Heuristic development of algorithms should be supported by formal mathematical analysis of their functionality. Thus this field will continue to provide exciting opportunities for research both in the development of methods and in their application to aerospace technology.

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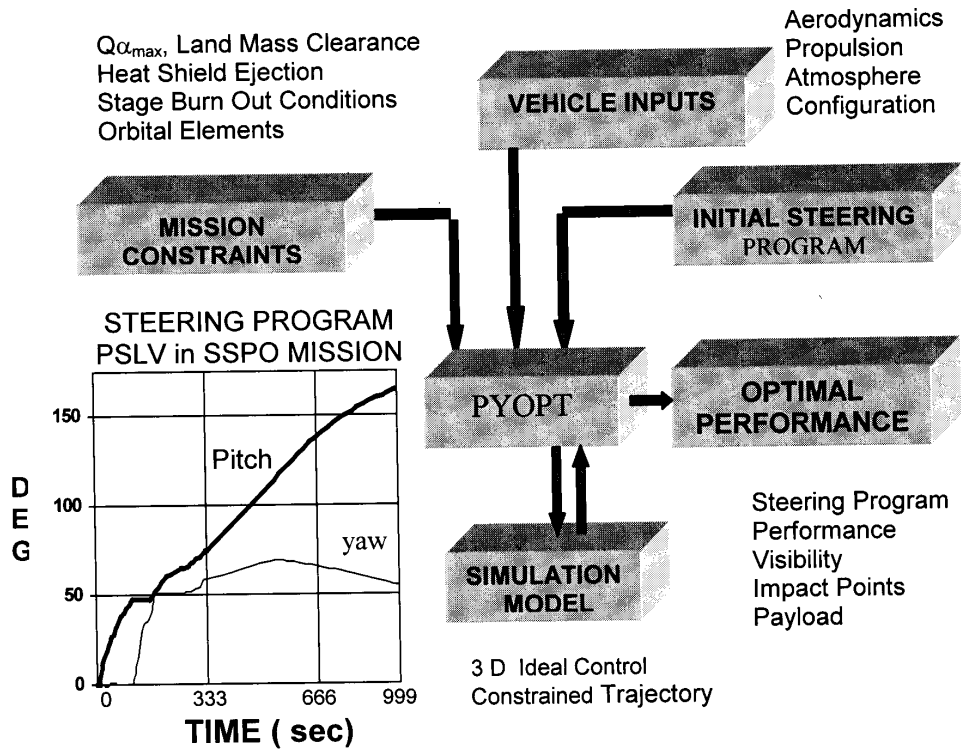


Fig. 1 The process of steering program design

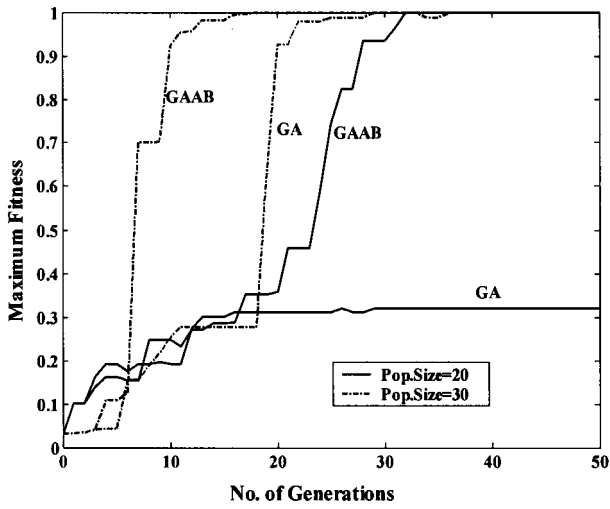


Fig. 2 Performance improvement with GAAB

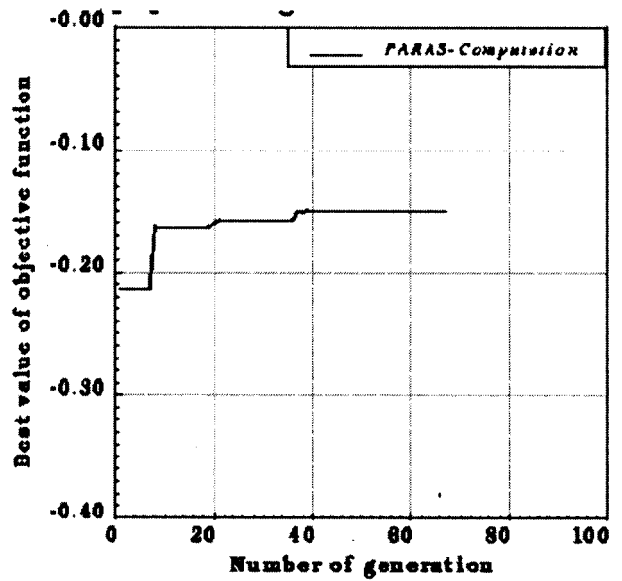


Fig. 5 Objective Function with Number of Generations

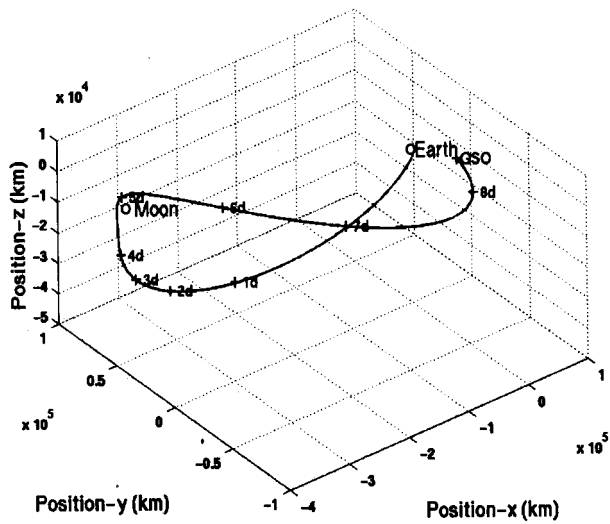


Fig. 3 Typical Optimal Gravity Assist Trajectory

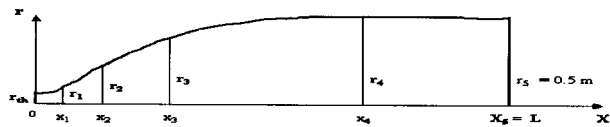


Fig. 4 Schematic of Hypersonic Wind Tunnel Nozzle Contour

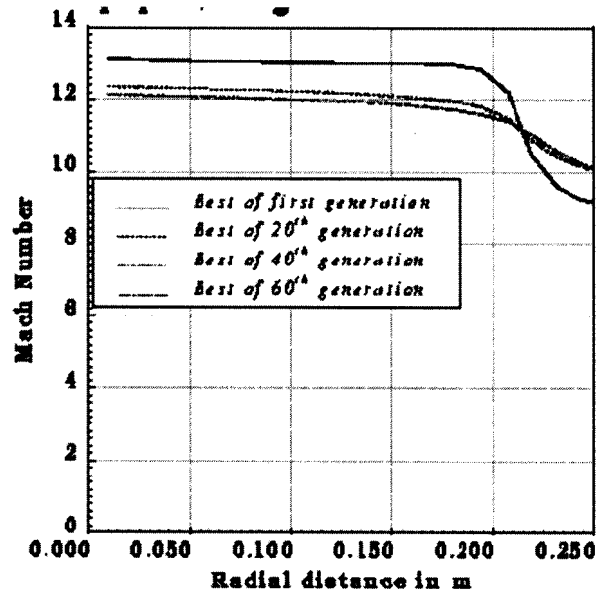


Fig. 6 Radial Mach Number Distribution at Nozzle Exit Plane

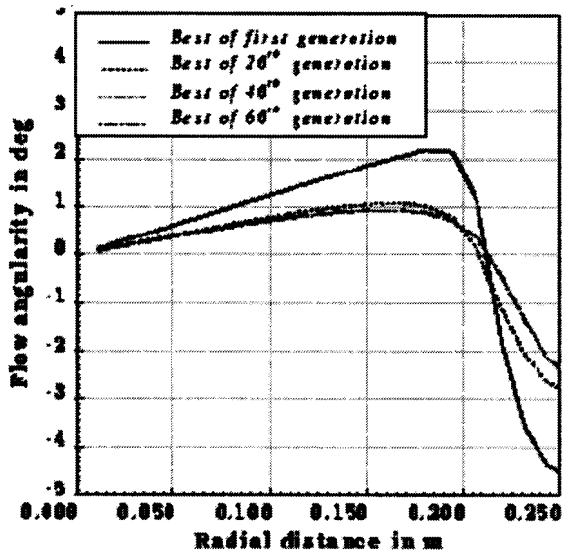


Fig. 7 Radial Variation of Flow Angularity at Nozzle Exit Plane

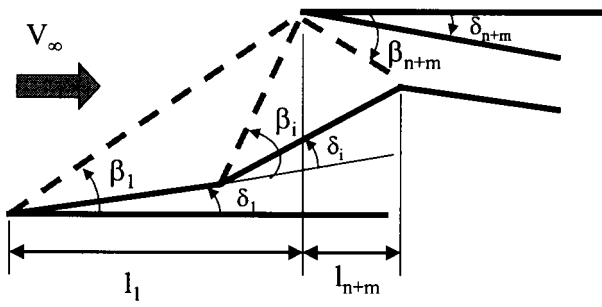


Fig. 8 Air-intake configuration parameters

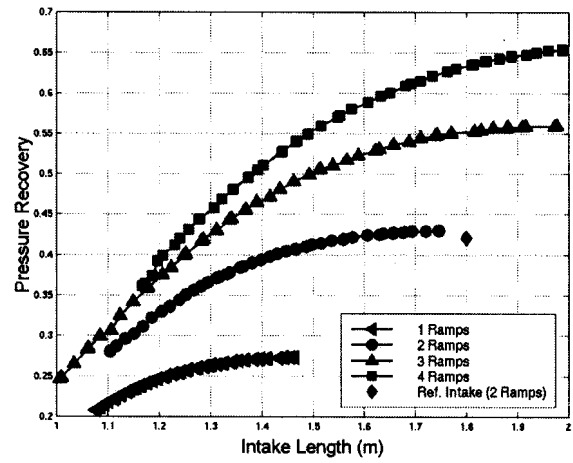


Fig. 9 Variation of intake length with pressure recovery

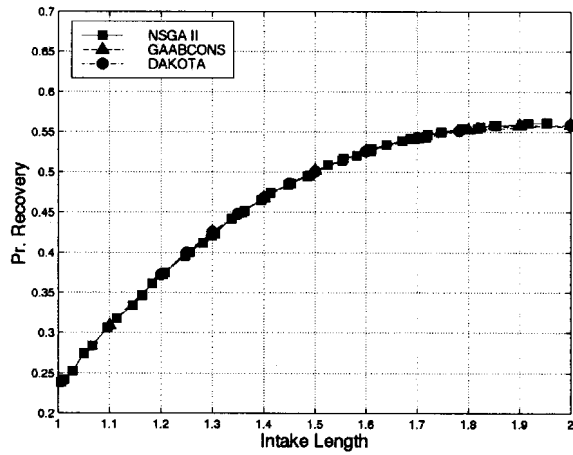


Fig. 10 Comparison of the Pareto-optimal front from various optimization codes