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OPTIMIZATION METHODS FOR LAUNCH VEHICLE CONCEPTUAL DESIGN

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Abstract. *The conceptual design process of a launch vehicle is highly coupled and non-hierarchical, and significant data exchange and iteration are often required among different disciplines (propulsion, aerodynamics, structure, trajectory, etc.). Choosing the launch vehicle optimal configuration requires its performance optimization. The performance optimization of a launch vehicle implies the tasks of system design and trajectory optimization. System design provides parameters like the number of stages and the engine sizing. Trajectory optimization gives the control vector that optimizes the performance for the chosen configuration. Ideally, design of vehicle and propulsion system and trajectory shaping should be iteratively refined together by a coupled multidisciplinary optimization scheme to obtain the optimum solution. The goal of this paper is to present a review of the Multidisciplinary Design Optimization (MDO) methods that have been applied to conceptual design of launch vehicles, showing their advantages and limitations. An overview of the launch vehicle design problem is also given in order to provide the necessary background for the further literature review and discussion.*

Keywords: *Launch Vehicle, Conceptual Design, Multidisciplinary Design Optimization.*

1 INTRODUCTION

The design of a launch vehicle, a large and complex system, requires making appropriate compromises to achieve balance among many coupled objectives such as high performance, safety, simple operation and low cost. The earlier in the design process that these compromises can be understood, the greater the potential for saving time and money and for reduction of technical and schedule risks.

The conceptual design is intended to reveal trends and allow relative comparisons among alternatives, early in the process, while design flexibility exists and before a large percentage of life cost are committed. For a specified mission requirement, the launch vehicle conceptual design process produces a configuration, traditionally driven toward high performance (mass optimized) or, according to a current tendency, toward low cost (cost optimized). Configuration specification includes definition of number of stages, external geometry and internal layout, technology selection, mass properties, performance estimates, operational scenario, and, perhaps, cost estimates.

At the conceptual design phase, the vehicle is defined with few details, and the relationships among design (vehicle) parameters and design objectives (metrics) are often not well understood or modelled. These intrinsic difficulties associated with conceptual design lead to a probably inefficient final design, leaving room for significant improvements in performance and reduction in life costs.

To improve results during the conceptual design phase, at least two emphases must be pursued (Lawrence et al., 1999):

1. improvement of disciplinary analysis, modelling and tools that capture, with sufficient fidelity, the major relationships among design variables and system objectives, and

2. the development of methods for coordinating the engineering analysis and optimizing the total launch vehicle system.

The second objective can be achieved by the application of Multidisciplinary Design Optimization (MDO) in the conceptual design level. A complex interrelation exists between mission requirements and constraints, trajectory shaping, propulsion, weights and loads with conflicting goals that have to be matched by an appropriate optimization strategy. MDO involves the coordination of multidisciplinary analysis to realize more effective solutions during the design and optimization of complex systems. It will allow system engineers to systematically explore the vast trade space in an intelligent manner and consider many more architectures during the conceptual design phase, before converging on the final design.

This paper presents a review of the MDO methods that have been applied to conceptual design of launch vehicles, showing their advantages and limitations. Initially, before the literature survey, it is given an overview of the launch vehicle conceptual design process.

2 LAUNCH VEHICLE CONCEPTUAL DESIGN PROCESS

In studying design optimization, it is important to distinguish between analysis and design. Analysis is the process of determining the response of a specified system to its environment. Design, on the other hand, is used to mean the actual process of defining the system. Clearly, analysis is a subproblem in the design process because this is how the adequacy of the design is evaluated (Vanderplaats, 1984).

The analyses involved in Launch Vehicle Design (LVD) are tightly coupled. Parameter variations that are intended to improve the performance of one subsystem may have adverse consequences in other areas. This way, the LVD process faces with the arduous task of equilibrating competing (sometimes, controversial) objectives for the vehicle, including safety, reliability, performance, operability, and cost. Objectives for safety, reliability, ease of operations, and design margin will increase system weights. On the other hand, designing for high performance and incorporating appropriate advanced technologies can lead to smaller, lighter systems.

Conceptual design refers to systems studies conducted early in the design process and intended to reveal trends and allow relative comparisons among alternatives. Such conceptual design studies provide quantitative data that can be used by decision makers while the design is still flexible and before the greatest share of life cycle costs are committed. At the beginning of conceptual design, often only the mission requirements (science, defense, commerce, etc.) are known, but, in some cases, additional information regarding vehicle concept, operational approach, and subsystem technologies may also be available.

The launch vehicle conceptual design process is highly coupled and non-hierarchical, often requiring significant data exchange and iteration among disciplines and disciplinary tools. Figure 1 depicts the coupling among various disciplines in launch vehicle design process, including cost estimation (Lawrence et al., 1999).

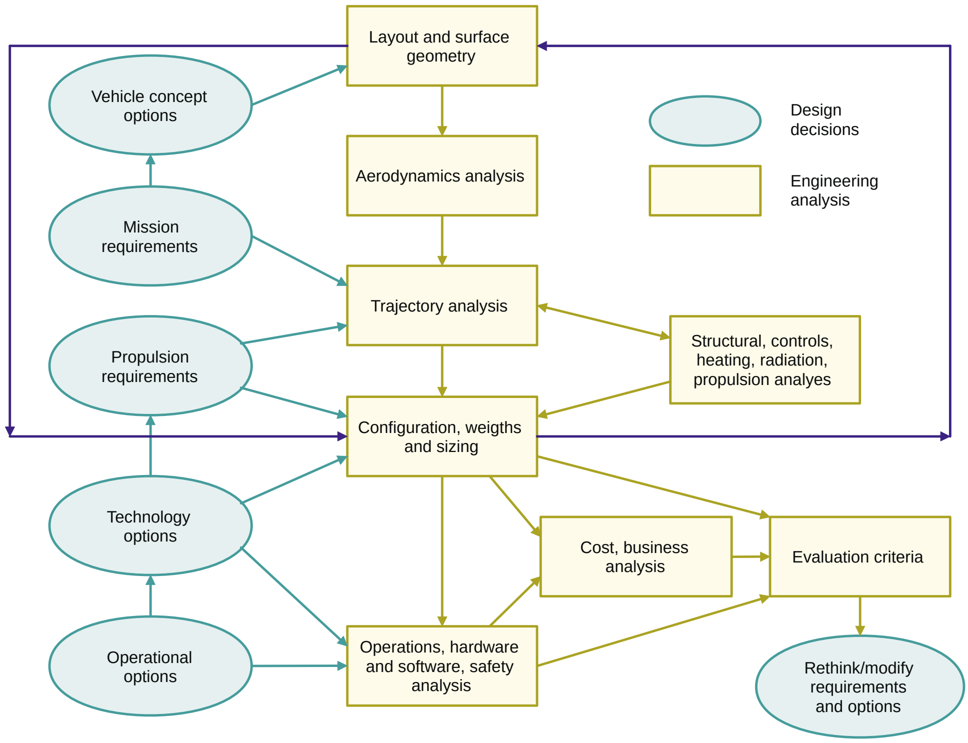

Figure 1: Coupling among disciplines in launch vehicle design process.

This simplified notion of the LVD process illustrates the variety of disciplines (subproblems) that make up the system-level design problem. The LVD process includes:

- specifying the mission requirements (e.g., payload size, mass, destination, environmental constraints, on-orbit operations, recovery, return);
- selecting a vehicle approach (e.g., rocket or air breather, winged or ballistic, piloted or automated, single or multiple stages, expendable or reusable);
- selecting associated operational scenarios (e.g., assembly, launch, recovery, refurbishment);
- selecting technologies (e.g., structural materials, thermal protection system, avionics, propulsion);
- creating a physical layout and surface geometry that will contain the payload, subsystems, and airborne support equipment;
- estimating the ascent and entry aerodynamics (subsonic, transonic, supersonic, hypersonic);
- calculating trajectories and the resulting flight environments;
- executing structural, controls, heating, radiation, and propulsion analyses based on the flight environment;
- estimating the vehicle weights, dimensions, and center of gravity based on layout, flight environment, and technology selection;
- analyzing operations, maintainability, hardware/software requirements, reliability, and safety based on operational scenario, vehicle configuration, and technologies;
- estimating life cycle costs (e.g., design, development, test, evaluation (DDT&E); production; operations; disposal) and business performance;

- calculating performance and programmatic evaluation criteria (metrics) used to compare alternatives;
- using these results to optimize and modify the overall system to better meet mission requirements and design objectives;
- continuing this process in an iterative manner to make downselects and deepen the vehicle definition as the concept evolves toward a mature design.

Determining the optimal configuration of a launch vehicle requires the evaluation of the interactions between the vehicle systems and the impact of these systems upon the vehicle's ability to perform the desired mission. This interaction, as shown in Fig. 2, leads to vehicle sizing/performance evaluations cycle (Szedula, 1996).

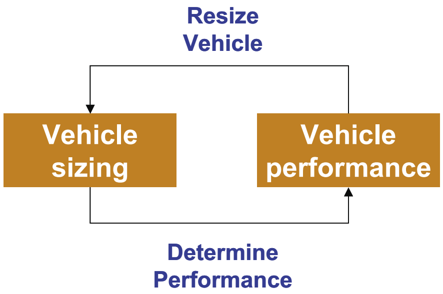

Figure 2: Vehicle sizing/performance cycle.

Before the availability of computer resources, the evaluation of the sizing/performance cycle was an essentially manual process. This manual process has two problems: i) the vehicle must be repeatedly sized and performance evaluated and ii) once sized, the vehicle may not be optimal (Szedula, 1996).

To obtain the optimum values of sizing parameters, the vehicle performance could be evaluated in order to examine the relative contribution of each parameter, whose value is changed while the the values of remaining parameters are kept fixed. This is referred as "one variable at a time" approach. This approach was used by Stanley et al. (1992b) to the conceptual design of a rocket-powered, two stage fully reusable launch vehicle has been performed as a part of Advanced Manned Launch System (AMLS) study by NASA. The reference geometry was chosen, the vehicle aerodynamics were evaluated, a propulsion system was selected, ascent and entry trajectories were analyzed, a centerline heating analysis was performed, baseline structural concepts and thermal protection system materials were selected, and a weight and sizing analysis was performed. After finalizing the reference vehicle, a series of parametric trade studies were also performed on the reference vehicle to determine the effect of varying major vehicle parameters.

In this "one variable at a time" approach, the relationships among the design variables are not considered in choosing optimum parameters. This may result in near-optimum configuration. Instead, if "all at the same time" approach will bring out more optimum configuration. This can be achieved by application of MDO methods in conceptual design process.

There is a good amount of work related to MDO methods for launch vehicle system and trajectory optimization. The highlights of some works available in literature are presented in next section.

3 LITERATURE REVIEW ON LAUNCH VEHICLE MDO WORKS

As stated earlier, choosing the optimal configuration requires launch vehicle performance (and, less often, cost) optimization. The performance optimization of launch vehicles implies the tasks of system design and trajectory optimization. System design provides parameters like the number of the stages and engine sizing. Trajectory optimization gives the control vector that optimizes the performance for the chosen configuration. Ideally, design of the vehicle and propulsion system and trajectory shaping should be iteratively refined together by a coupled multidisciplinary optimization scheme to obtain optimum solution.

One approach to optimize vehicle performance is to collect all elements of the trajectory control vector and system design variables in one vector of optimization parameters to be manipulated by an appropriate non-linear programming algorithm. This approach has been applied successfully to ascent mission of rocket powered single-stage-to-orbit (SSTO) vehicle in a multidisciplinary design environment (Braun et al., 1995; Braun and Moore, 1997). These studies focus on development of rapid multidisciplinary analysis and optimization capability for launch vehicle design. To simplify the analysis, several disciplines were decoupled and propulsion, performance and weights and sizing were considered for the study. For propulsion system, the parameters supplied by Pratt & Whitney were used, after regression analysis. The Program to Optimize Simulated Trajectories (POST) was used for trajectory optimization. An existing vehicle geometry and aerodynamic database were used and data from aerodynamics, structures, heating and other subsystems were fixed or scaled appropriately.

Two architecture referred as "iterative loop solution strategy" and "sequential compatibility constraint solution" are addressed in (Braun et al., 1995) with 40 design variables and 13 constraints. Iterative loop method is depicted in Fig. 3. Here an iterative loop is set up between the trajectory and weights and sizing disciplines. Values of GLOW, S_{ref}, the base diameter and the landed weight are used as loop convergence criteria. This formulation may be referred "multidisciplinary feasible" since for each set of design variables the looped analysis return a design candidate that is consistent across disciplinary boundaries.

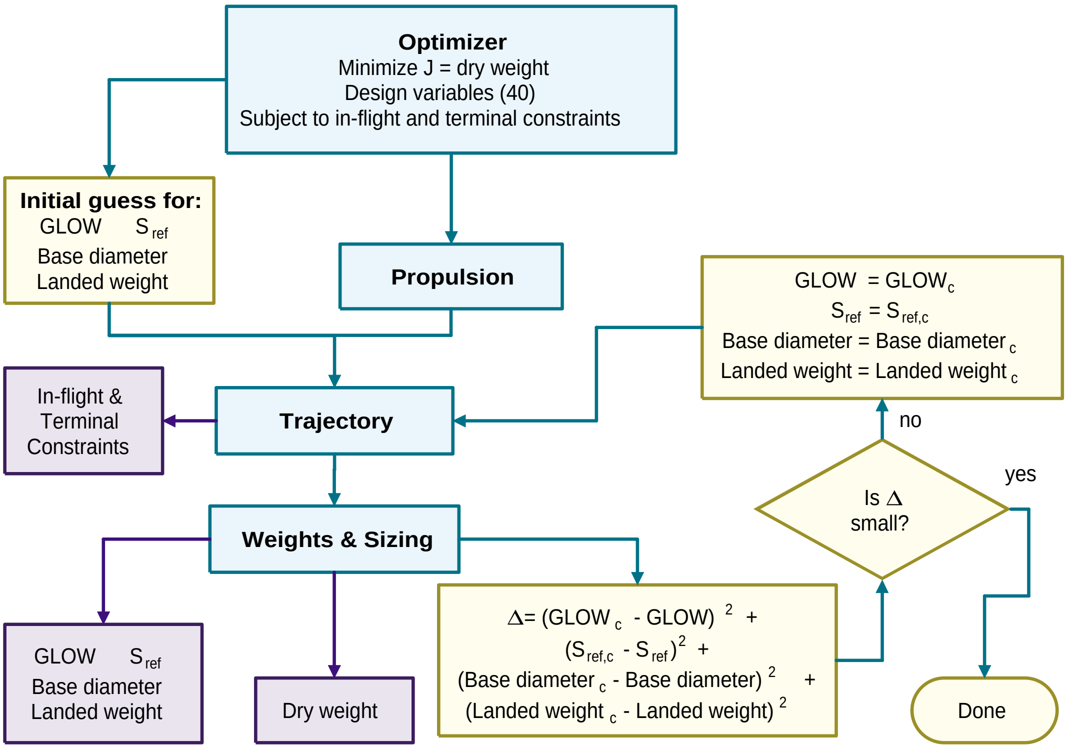

Figure 3: Iterative loop MDO strategy.

In the sequential compatibility constraint method, the iterative loop is replaced by use of auxiliary variables and compatibility constraints. As shown in Fig. 4, an auxiliary variable and a compatibility constraint are added to the optimization-problem statement for each variable that is required as input to one discipline but is computed by another discipline later in the analysis sequence. Hence, S_{ref}, GLOW, the base diameter, and the landed weight are added as design variables. In this manner, the iterative loop is removed, and the configuration control becomes an additional task of the optimizer. By satisfying these four compatibility constraints, consistent vehicle model is guaranteed. However, as opposed to the iterative loop approach, compatibility is required at the solution only. This type of approach may be referred to as "simultaneous analysis and design," since both a consistent and an optimum set of design variables converged upon simultaneously.

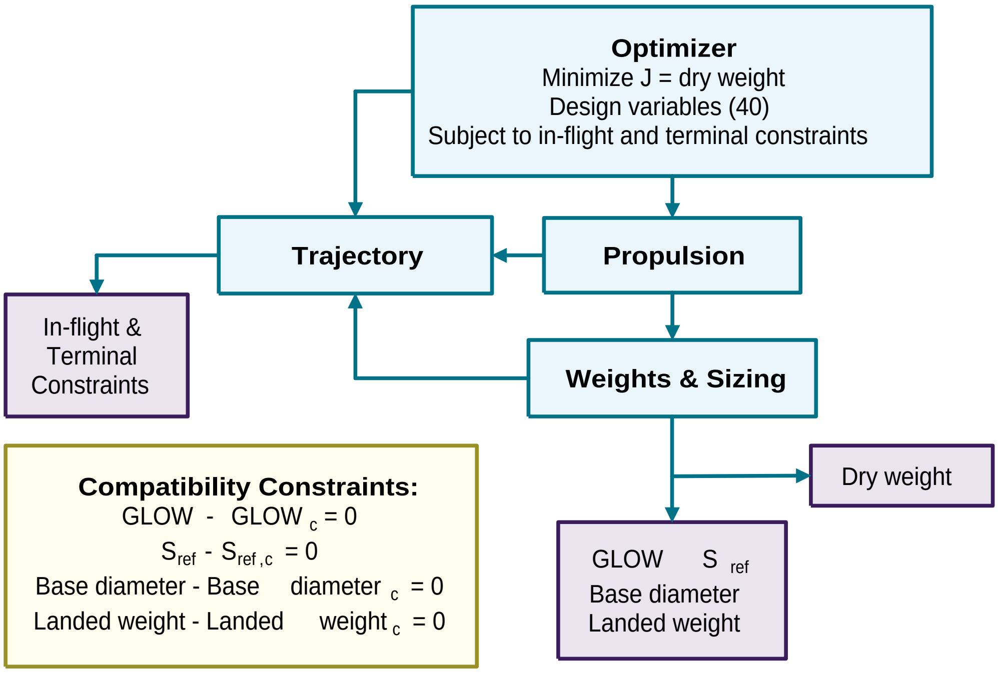

Figure 4: Sequential compatibility constraint solution.

The study described by Braun et al. (1995) indicates that use of the sequential compatibility constraint approach has several advantages relative to the iterative-loop approach. These advantages include i) being 3–4 times more computationally efficient ii) providing greater flexibility in the way in which consistency is maintained across disciplinary boundaries, and iii) a smoother design space. The only disadvantage of the compatibility constraint approach is in situations when the optimizer terminates without reaching the solution on account of poor scaling or model non-smoothness. Because multidisciplinary feasibility is only guaranteed at a solution in this approach, the design information could be invalid.

Optimization of system and trajectory together was applied to Reusable launch Vehicle (RLV) by Tsuchiya and Mori (2002). In their study, MDO method was applied to choose best among seven typical concepts of RLV. The design variables representing geometry and shape of vehicles, flight performance of flight trajectories were considered as design variables. The MDO architecture used here is similar to the "sequential compatibility constraint solution". The study concluded that the proposed MDO optimization method was effective for the design problem considered.

Collaborative optimization is a new design architecture whose characteristics are well suited to large-scale, distributed design. It was used, for example, by Braun and Moore (1997) to solve a problem with 95 design variables (23 interdisciplinary) and 16 constraints. The fundamental concept behind the development of this architecture is the belief that disciplinary experts should be able to contribute to the design process while not having to fully address local changes imposed by other groups of the system. To facilitate this decentralized design approach, the problem is decomposed into subproblems along domain-specific boundaries, as illustrated by Fig. 5. Through subspace optimization, each group is given control over its own set of local design variables and is charged with satisfying its own domain-specific constraints. The objective of each subproblem is to reach agreement with the other groups on values of the interdisciplinary variables. A system-level optimizer is employed to orchestrate this interdisciplinary compatibility process while minimizing the overall objective. This decomposition strategy allows for the use of existing disciplinary analysis without major modification and is also well suited to parallel execution across a network of heterogeneous computers.

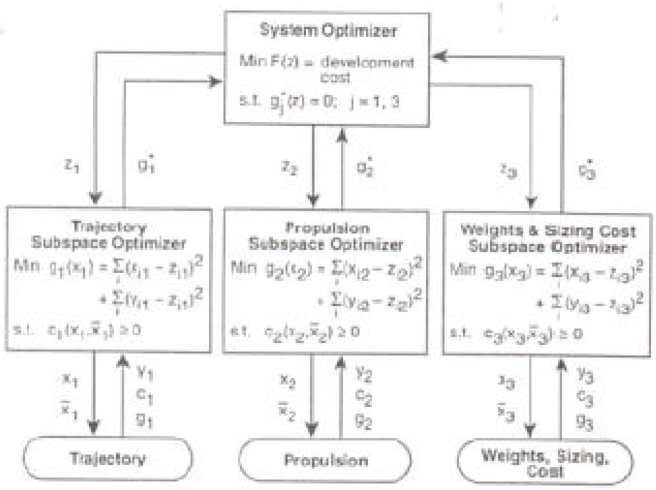

Figure 5: Collaborative optimization architecture for launch vehicle design.

Advantages of this collaborative architecture are that it i) may not require either modification of codes or explicit integration into an automated computing framework, ii) allows subproblems to be optimized by the best-suited method, iii) allows for the addition or modification of subproblems, and iv) can efficiently accommodate a large number of variables. Table 1 shows the performance comparison between the above three methods for the mentioned design problem. Communication requirements are minimal because knowledge of the other groups' constraints or local design variables is not required.

Table 1: Comparisons of MDO strategies in launch vehicle design.

MDO Architecture	**Function Evaluation**	**Modification Time, month**	**Communication Requirements**
Iterative Method	10482	4	66
Compatibility Constraint	3182	3	65
Collaborative	3125–24840	1	23

Although these MDO architectures had been applied successfully to the ascent mission of single-stage vehicles, it has shown poor convergence properties even for the less complex mission example of an expendable multistage rocket launcher, when major system design parameters such as the mass split of stages or engine sizing were included to optimize trajectory control and vehicle parameters simultaneously (Rahn and Schöttle, 1996).

An approach that overcome this difficulty is a *multistep sequential optimization procedure* (Schöttle and Hilleshcimer, 1991). This multistep sequential procedure, outlined in Fig. 6, consists of a performance optimization cycle (inner loop) and a vehicle design cycle (outer loop). The first loop uses the data of the latter to determine the control functions and major system parameters yielding the optimum performance. This automatic inner loop responds to varying vehicle size needs as long as the departure from the preset design (outer loop) remains small. Otherwise, a vehicle redesign including system modifications and reevaluation of the aerodynamic coefficients (which are held constant in the inner optimization cycle) is performed in separate computations in the outer iteration loop. The latter requires manual interaction and is supported by graphic interface tools. This scheme outlined above is applied to enhance the performance of a reusable rocket launcher which is part of Ariane X family (Hillesheimer et al., 1992).

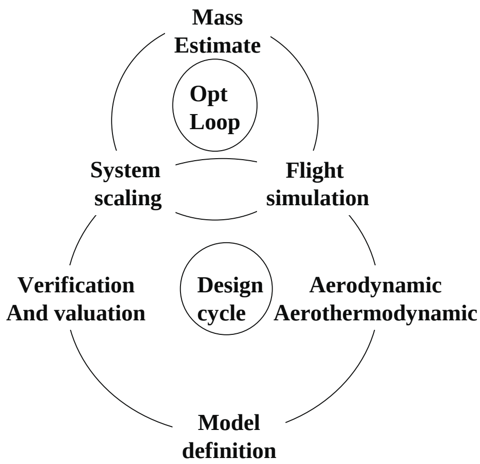

Figure 6: Multistep sequential procedure.

There are two design softwares for solid motor missile which are based on the schemes similar to multistep sequential optimization process: SWORD (Strategic Weapon Optimization for Rapid Design), developed by Lockheed Missile Design and Space Co. (Hempel et al., 1994); and FASTPASS (Flexible Analysis for Synthesis Trajectory and Performance for Advanced Space Systems), developed by Lockheed Martin Astronautics (Szedula, 1996).

Though this scheme was able to solve the optimization problem of a two-stage, winged rocket launch vehicle designed for vertical takeoff, severe convergence problems were encountered when it was applied to the more complex mission of an airbreathing Sänger-type STS (Rahn and Schötlle, 1996). These difficulties were attributed in part to different performance sensitivities of the various flight phases, controls, and major system design parameters, and to scaling problems.

A decomposition approach was used by Rahn and Schötlle (1996) to solve the overall optimization problem of a Sänger-type launch system. Decomposition of a mission means partitioning the trajectory into subarcs such that each mission segment can be optimized independently. These subproblems constitute the first level of optimization. A second-level controller is then used to optimize the entire mission. Hence, a two-level optimization procedure results, with the master-level algorithm optimally coordinating the solution of the subproblems. The schematic diagram of decomposition of segments and the decomposition formulation for the two stage to which stage missions are shown in Fig. 7 and Fig. 8, respectively.

This algorithm was applied to determine the optimal ascent trajectory of an airbreathing launch vehicle of Sänger-type that delivers a maximum payload to desired orbit while staging conditions and mass distribution between the two stages of the vehicle was unknown and had to be determined. The study demonstrated the capability of the decomposition method to successfully optimize the entire mission and the major design variables.

MDO methods can be broadly divided into three groups: 1) Parametric methods based on Design of Experiments (DOE) techniques; 2) Gradient or Calculus based methods; and 3) Stochastic methods such as geometric algorithm and simulated annealing. Parametric methods

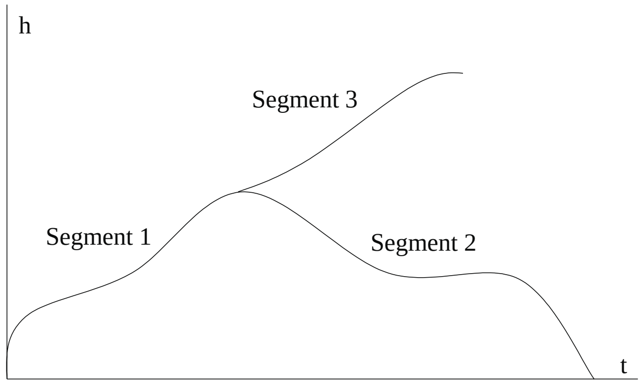

Figure 7: Schematic diagram of decomposition of segments.

Master Problem: Maximize upper-stage payload mass

Independent variables:
- Staging Mach number
- Longitude at staging
- Load factor at pull-up
- Time interval for pull-up

Subproblem 1:	**Subproblem 2:**	**Subproblem 3:**
Minimize: Booster stage ascent propellant	**Minimize:** Booster stage fly-back propellant	**Minimize:** Orbiter ascent propellant
Subject to: Staging Mach no. (master contr.) Staging longitude (master contr.) Latitude at staging heading staging	**Subject to:** Max flight acceleration Max dynamic pressure End head towards landing site	**Subject to:** Max long. Flight acceleration Perigee velocity Perigee altitude Perigee path angle
Independent variables: flight heading after take-off supersonic cruise flight length bank angle control parameter determines the length of the turn flight.	**Independent variables:** Angle of attack control Bank angle control Parameter determines the length of the turn flight.	**Independent variables:** Angle of attack control

Figure 8: Decomposition formulation for a two-stage-to-orbit mission.

as well as gradient based methods are applicable at conceptual design phase (Lawrence et al., 1996). The above-mentioned studies are all based on gradient based optimization methods.

Launch vehicle conceptual design studies have been carried out using parametric optimization method. Stanley et al. (1992a) uses parametric optimization in a study which employs Taguchi design method to determine the proper levels of a variety of engine and vehicle parameter for a single-stage-to-orbit vehicle. Such study considers five design parameters. The configuration selection for rocket powered single-stage vehicle configuration using Response Surface Method (RSM) was presented in (Stanley et al., 1994). Five configuration parameters that greatly affect the entry vehicle flying qualities and vehicle weight were considered for study. RSM was used to determine the minimum dry weight entry vehicle to meet constraints on performance.

Olds and Walberg (1993) has applied Taguchi's method to conceptual design of a conical (winged-cone) single-stage-to-orbit launch vehicle. Taguchi's method was used to evaluate the effects of changing 8 design variables (2 of which were discrete) in an "all at the same time" approach. Design variables pertained to both the vehicle geometry (cone half-angle, engine cowl wrap around angle) and trajectory parameters (dynamic pressure limits, heating rate limits, and airbreathing mode to rocket mode transition Mach number). The vehicle payload was fixed at 4,500 kg to 185 km circular polar orbit. Vehicle dry weight and gross weight were determined for each of the 27 point designs performed.

Anderson et al. (2001) have investigated the potential of using a multidisciplinary genetic algorithm approach to the design of a solid rocket motor propulsion system as a component within an overall missile system. Aerodynamics and trajectory performance disciplines were considered in their study.

In the early stages of the design process of aerospace vehicles, as it should be clear up to now, the search for optimal configurations encompasses a broad range of possibilities, and the use of local optimization tools may risk missing the best designs. Therefore, global optimization methods are attractive for the early design stage. Unfortunately, global design optimization usually requires the evaluation of a very large number of designs, a formidable computational challenge. Using design of experiments (DOE) theory, the number of sampled points can be significantly reduced. Even using a relatively small data set generated cheaply from DOE, there may be many important and potentially optimal regions of feasibility left uncharacterized for a complex design problem. Baker et al. (2000), for example, uses a highly effective Lipschitzian global optimization algorithm in the multidisciplinary optimization of a High Speed Civil Transport (HSCT).

4 FINAL REMARKS AND CONCLUSIONS

In previous sections an overview of the launch vehicle design problem and the optimization methods was given to provide background and terminology for discussing the literature review that was presented in the sequence. This section presents some additional comments and conclusions about the theme focused here.

Conducting a multidisciplinary trade study by conventional methods is a time consuming process dominated by the reformatting, transforming, and translating of data between design disciplines and analysis modules. The open objective is to develop design tools that more efficiently facilitate integrated design and optimization (MDO).

Multidisciplinary design problems are by their very nature extremely interconnected and nonlinear. Therefore, in searching for an optimum solution, one cannot simply assume that a given solution is optimal in the global sense simply because the solution may be optimal locally. The problem then becomes one of not simply 'climbing the hill' but rather, first finding the hill that is the tallest, and then climbing it. The methods employed to solve this type of problem must therefore have the ability to either avoid local optima all together or escape them once they are encountered in order to be effective.

This fact alone may put traditional gradient-based methods at a disadvantage, as the optimum solution that they locate is dependant largely upon the point in the function space at which they started. Non-gradient based methods such as genetic algorithms, for instance, may better suited to addressing the problem of locating a global optimum, but typically do not converge to a solution as effectively as gradient-based methods. Ideally, a non-gradient based method might be used to determine which is the tallest hill, and a gradient based method to climb it.

A 'hybrid' optimization strategy such as this may allow dissimilar methods to be employed in a complimentary fashion in order to most efficiently address the problem. Theoretically, relative strengths of these methods are exploited while their respective weaknesses are suppressed, thus yielding the analytical benefits of both. In the end, several solution strategies may yield successful results, however, the most effective method to solve a given problem will ultimately depend on the specifics of the problem itself, and of course every problem, and every design, will be different.

A variation on the theme of direct application of optimization techniques involves the use of a Design of Experiments (DOE) to allow the user to adequately cover all the necessary trade space of the design envelope without running unnecessary cases. DOE tools save time by only running the design cases needed to form an accurate picture of the overall design. However, even using a relatively small data set generated cheaply from DOE, there may be many important and potentially optimal regions of feasibility left uncharacterized for a complex design problem. Once the set of points to be evaluated is constructed, either through statistical (DOE) methods or via a direct search global optimizer, the points in the set can be evaluated adequately. Response Surface Methods (RSM) are used as a follow-on technique to build a mathematical model of the design space such that optimization search algorithms can quickly and easily find the best solution.

The conceptual design of launch vehicle involves various disciplines, highly coupled, in a non-hierarchal way. Considering all disciplines with adequate fidelity model at conceptual design phase improves the efficiency of launch vehicle designed. The disciplinary analysis could be done with physics-based or statistics-based models, with more or less fidelity levels. Although the incorporation of high-fidelity models into conceptual LVD could be desirable in some instances, in other, however, it could be more convenient to use methods having less fidelity: the overall consistency is always important. Inaccurate modelling cannot be corrected by optimization methods or by powerful integration frameworks. Advances in the latter two alone would serve only to create questionable estimates at a faster rate.

In short, implementation of MDO from the conceptual design phase can produce more optimal solutions and provide greater insight into a given design trade space. The optimization method and the fidelity level of the disciplinary models should be both compatible with the nature of the problem to be analyzed and the type of response to be obtained.

Now with availability of various methods, good amount of work related to MDO in launch vehicle design appear in literature. This literature survey reveals that MDO works related to launch vehicle conceptual design, that is, simultaneous optimization of system and trajectory, are limited to enhancement of the existing reference vehicle systems or subsystem optimization with respect to vehicle performance. This may be attributed to the focused effort on the Advanced Manned Launch System (AMLS) activity since 1988. Two vehicles, a single-stage and other two-stage, were used for this AMLS mission and all further design studies are to optimize the performance of these configurations. Also, other recently developed vehicles are designed by evolution strategy.

In spite of the diversity of possibilities, an MDO method that has 'zero order' sizing capability would be useful in developing a new multi-stage vehicle. That is, given the range of realizable mass fraction and specific impulse, the scheme should be able to decide the number of stages, mass and propellant fraction and iterate this vehicle and propulsion system and trajectory shaping and give optimum configuration and trajectory that meets the specification. This would be useful when no propulsion system or technological constraints are identified and the initial trade space is being defined. This scheme may come up with a design that is non-intuitive and much better than traditional design technique. Therefore, this could be an interesting point to future research work.

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