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EXTERNAL CONFIGURATION DESIGN AND AERODYNAMIC OPTIMIZATION OF MODULAR GUIDED MUNITIONS

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ABSTRACT

Guided munitions, also known as gliding missiles are not stand alone systems; rather, they are converted from a dummy body with the help of guidance kits. Guided munitions, unlike air-to-air or cruise missiles, are used in large numbers during military activities. Guided munitions can be divided into two main sub-categories that have either strakes or wings. First group provides guidance and stability with use of strakes. These type of missiles used for relatively short ranges. Second group has wings instead of strakes in order to increase the missile's range. Missiles in first subcategory may be converted to second group by changing their strakes with wings. For such a modification, both versions of that missile should be optimized together during the conceptual design phase. The main focus of this study is to obtain a conceptual design tool, by employing Genetic Algorithm with aerodynamic analysis, that optimizes a guided munition geometry which can be used as both versions, with strakes or wings, in terms of aerodynamics related objectives.

INTRODUCTION

The number of missile projects has increased in recent years. In this rapidly developing area, there are several challenges affecting the design phase. High time pressure, as the product delivery dates are very strict in military projects, updating requirements during conceptual design phase and storage efficiency are the most influential challenges that direct the design phase.

Some outer geometry optimization studies and design tools, that aim to cope with these challenges, could be found by conducting the literature survey. McDonnell Douglas Corporation (MDC) and the NASA Langley Research Center (LaRC) have together developed a design tool to conduct performance analysis and optimize the hypersonic air breathing vehicles, [Alberico, 1992]. This tool assesses the performance between flight conditions such as speed and altitude. Furthermore, Low Observables Design Synthesis Tool (LODST), which is a system design tool for the conceptual design phase, was created by Bennett, [Bennett, 1997]. Both the analytical and semi-empirical methods are used to predict the propulsion

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system design characteristics, missile aerodynamics and mass budgeting in LODST. Another design tool developed by Aytar-Ortaç [Aytar-Ortaç, 2002] focused on the conceptual design of unguided missiles. Maximum range, minimum dispersion and maximum warhead effectiveness were chosen as the design objectives. Another design tool is EXCON, which dealt with air-to-air, air-to-ground and surface to surface missile optimization with a 3 DOF simulation based on Genetic Algorithm and developed in 2009 [Tanıl, 2009]. In another thesis study in METU, Dede [Dede, 2011] utilized both simulated annealing and genetic algorithms individually and a hybrid algorithm, which is a combination of these two approaches. The tool developed was valid for turbojet powered air-to-ground missiles. The aim of another study by Karakoç in METU [Karakoç, 2011] was multi-disciplinary design and optimization of an air-to-surface turbojet powered missile with the objectives of maximum flight range and minimum radar cross section area, as the minimum radar cross section is important for survivability.

In this study, it is aimed to develop a design tool that can optimize the gliding missile's outer geometry while taking into consideration the modularity of lifting surfaces by investigating two different versions of the same configuration. The most important aspect of modularity is the fact that it is very beneficial in widening the scope of operational concepts. In the meantime, it enables to carry out an operation with the most cost-effective missile that can fulfill the mission. The version with strakes is defined as the 1st version (Figure 1) whereas the version which has wings defined as the 2nd version (Figure 2).

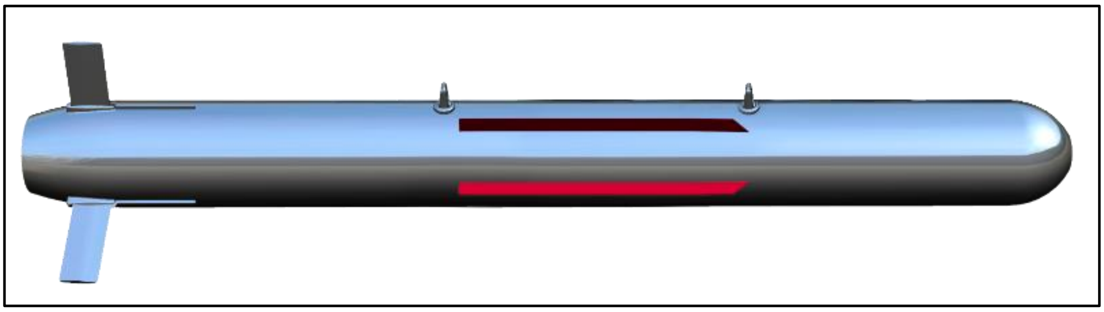

Figure 1. 1st Version of the Missile (with strakes)

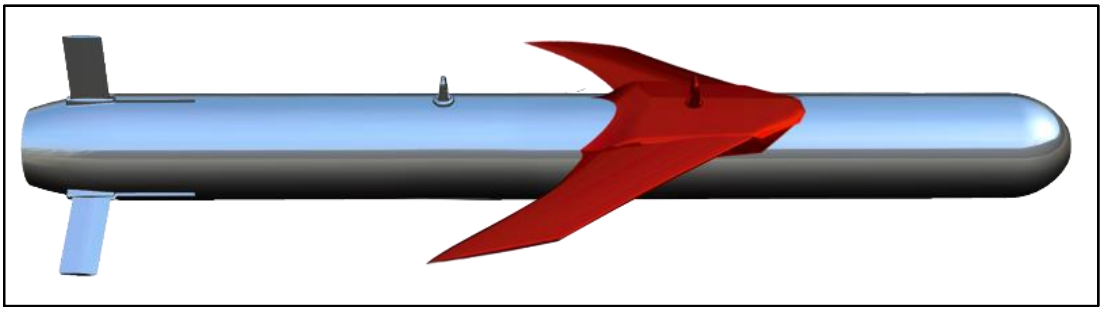

Figure 2. 2nd Version of the Missile (with wings)

METHOD

The design of a missile is an iterative process. A number of design iterations are required to achieve a balanced optimum design satisfying the design objectives. Together with fulfilling the performance requirements such as range and maneuverability, the design must also be compatible with the specified constraints such as total mass, stability, and control.

The optimization cycle starts with selecting the design objective functions and their weights against each other. For different mission and scenario definitions, different objectives may become more important. In conjunction with the objectives, also the constraints of the system should be defined at the beginning. With some selected basic geometrical parameters, the outer geometry of a missile can be defined. By using the appropriate Design of Experiment (DoE) method, an initial design space is generated. After the initial design is evaluated, the optimization algorithm generates new designs with different values of parameters. All of the designs should be aerodynamically analyzed. For this purpose, USAF Missile DATCOM software [Blake, W. B, et al., 2011] tool is used in this study. The design and optimization procedure used in this study is shown in Figure 3.

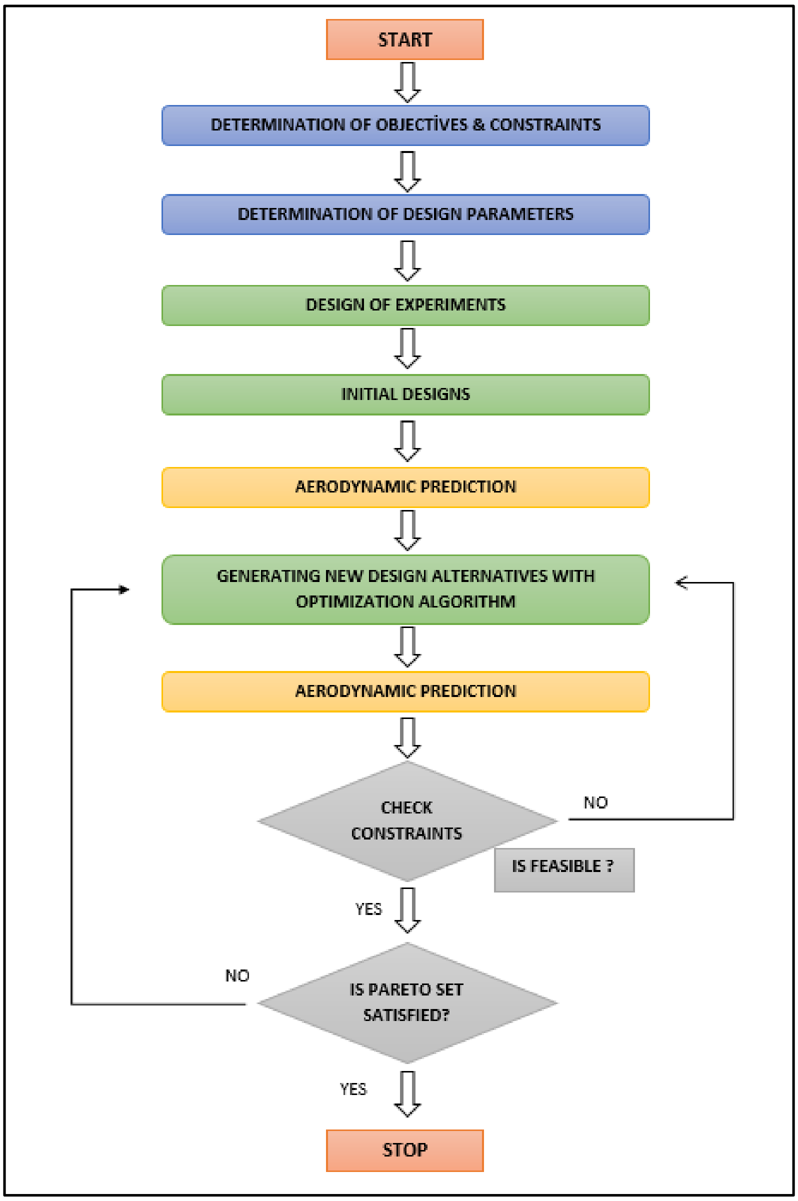

Figure 3. Design and Optimization Procedure

Objectives and Constraints

During the conceptual design work investigated in this study, the following design objectives and constraints are considered.

Objectives:

The main objectives of this study is to maximize both the range and the maneuverability of the modular gliding missile. A guided munition is a special kind of missile that has no propulsion system. As a result, the motion of guided munitions is defined as gliding motion. Therefore, for maximum range the Lift-to-Drag ratio at trim condition ($\boldsymbol{C_L/C_{D@trim}}$) should be maximized.

Lift and thrust are the main forces that can be used for maneuverability of any missile. However, as there is no propulsion system in a guided munition as stated before, the guided munitions can solely use the component of lift force ($\boldsymbol{C_L}$) for maneuverability. The maximum values of CL, that can be obtained without confronting any nonlinearities, are termed as maximum usable lift coefficient ($\boldsymbol{C_{L_{\max\_usable}}}$). The most typical example of this non linearities is the large local gradient changes of static stability as a function of AoA, so called local pitch up [Osterhuber, 2011]. A qualitative example of a local pitch up, strong localized change in pitching moment derivative ($\boldsymbol{C_{m_\alpha}}$) wrt AoA is given in Figure 4.

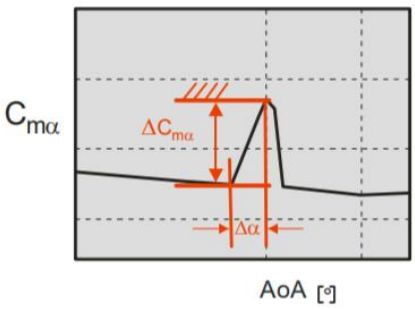

Figure 4. Local Pitch Up [Osterhuber, 2011]

In order to avoid the influence of nonlinear aerodynamic characteristics the necessary equation is given below.

$$\boldsymbol{dC_{m_\alpha}/d\alpha \leq 0.1}$$

The point where the local gradient of static stability exceeds 0.1 is the upper limit for the angle of attack of missile. This AoA limit may be different for different Mach Numbers. Exemplary matrix demonstrating the usable lift coefficients ($\boldsymbol{C_{L_{\max\_usable}}}$) in green fillings is given in Figure 5.

	α=0°	α=1°	α=2°	α=3°	α=4°	α=5°	α=6°	α=7°	α=8°	α=10°
M = 0.1	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.3	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.5	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.6	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.7	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.8	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 0.9	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 1.0	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 1.1	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx
M = 1.2	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx	C_L=xx

Figure 5. Usable Lift Coefficients Matrix

One of the design objectives of this thesis is maneuverability. Design variable that affects the maneuverability is the maximum usable lift coefficient ($C_{L_{\max\_usable}}$). In order to maximize maneuverability, lift coefficient shall be increased. Maneuverability is a more important asset for the first missile version with the strakes (V1) than for the second version with wings (V2) because of the fact that the second version has more time to fly towards the target.

The other design objective used in this study is range. To maximize the range, the design variable that shall be increased is Lift-to-Drag ratio at the trim condition, ($C_L/C_{D@trim}$). The main reason to add wings to the basic configuration of the missile is to increase range. Therefore, the range is more important for the second version with wings (V2) than it is for the first version with strakes (V1).

Because of the above mentioned reasons, the two objective functions are defined as follows:

$$\mathbf{OBJ\ 1} = C_{L_{\max\_usable}} = \mathbf{P1} * C_{L_{\max\_usable}}\,(\mathbf{V1}) + \mathbf{P2} * C_{L_{\max\_usable}}\,(\mathbf{V2})$$

Where, P1 = 0.7 and P2 = 0.3 in this study for the first objective, and

$$\mathbf{OBJ\ 2} = (C_L/C_D)_{@trim} = \mathbf{P1} * (C_L/C_D)_{@trim}\,(\mathbf{V1}) + \mathbf{P2} * (C_L/C_D)_{@trim}\,(\mathbf{V2})$$

Where, P1 = 0.3 and P2 = 0.7 in this study for the second objective.

<u>Constraints:</u>

1) Platform Integration Constraints:

$$\boldsymbol{Platform\ Capability} \geq \boldsymbol{Total\ Length}$$
$$\boldsymbol{Platform\ Capability} \geq \boldsymbol{WingSpan}$$
$$\boldsymbol{Platform\ Capability} \geq \boldsymbol{Diameter}$$

2) Structural Constraint: Missile's body fineness ratio should be within the given interval [Fleeman E. L., 2001],

$$\mathbf{5} < \frac{\boldsymbol{length}}{\boldsymbol{diameter}} < \mathbf{25}$$

3) Static Stability Constraint: For longitudinal static stability, following conditions should be satisfied,

$$C_{m_\alpha} < \mathbf{0}$$

$$C_{m_{\alpha=0^\circ}} > \mathbf{0} \qquad \text{(In order to have trim condition)}$$

4) Control Effectiveness Constraint [Fleeman E. L., 2001],

$$\frac{C_{m_\delta}}{C_{m_\alpha}} = \frac{\Delta\alpha}{\Delta\delta} > \mathbf{1}$$

Optimization Algorithm

Genetic Algorithm Method have recently shown promising results in solving multi-objective design problems and are easily implemented compared to the deterministic methods. Genetic Algorithm has already proved itself in multi objective optimization with several studies, by finding good solutions in reasonable amounts of time [Cantu-Paz, 2001]. Though, conventional deterministic algorithms may also be alternatives of search algorithms, they are not preferable for complex optimization problems. Thus, genetic algorithm is used in this study.

Customized genetic algorithms are especially useful for finding accurate solutions to multi-objective problems since they may evaluate various solutions in a single simulation. The solution of multi-objective problems using genetic algorithm give rise to set of trade-offs which referred as Pareto-optimal set. Each of this solutions are optimal, and without preferring one objective to another, none of the solutions is better than the others. [Fonseca & Fleming, 1993]. Although the process of genetic algorithm is random as in the nature, in this technique level of probability can be determined [Goldberg, 1989].

As stated before genetic algorithms start with an initial set of individuals, referred as population. The necessary initial population is created by DOEs. Each individual in the population is called as chromosome and represents a solution to the optimization problem. In this thesis, each possible outer geometry of the missile can be referred as chromosomes. An individual is characterized by a set of parameters (variables) known as genes. Body diameter, body length, configuration (+ or X), airfoil type etc. can be thinked of as genes. Genes are joined into a string to form chromosome (solution).

Terminology used in genetics algorithm is taken from biology. Gene, chromosome and population, are shown in Figure **6**.

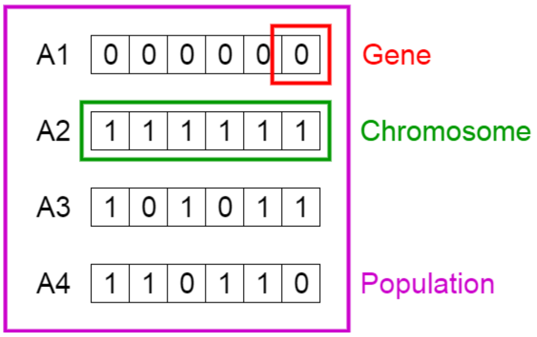

Figure 6. Gene, Chromosome and Population in Genetic Algorithm [Zitzler E., 1999]

Generally, there are four main operators of Evolutionary Algorithms, known as selection, crossover, mutation and elitism. Selection is the genetic algorithm's primary inspiration in nature. In selection phase, the fittest individuals are selected and they have a higher possibility to pass their genes to the next generation. The selection is based on fitness score which is obtained by comparing the chromosomes. In this manner, genes that encode beneficial characteristics are propagated through subsequent generations. Hopefully, the algorithm converges to optimum solution after several generations [Gen & Cheng 1997].

Following the selection phase, the solutions are altered by either crossover, mutation or both, aiming to obtain new solutions from existing ones. It can be considered as the most significant phase for Genetic Algorithm. A crossover point is chosen randomly for each pair of parents to be combined to create certain number of offspring. The new generation is created by exchanging the genes of the parents. The new offspring are added to the population, leading population to converge by making the chromosomes in the population similar to each other. The mutation on the other hand, conducts random changes in the chromosomes at the gene level according to the given mutation rate. This means that mutation introduces genetic diversity into the population. This also increases the robustness, the ability to reach the absolute extreme of the objective function, of the algorithm. [Konak A., Coit D. W., Smith A. E].

Elitism, apart from the mentioned above, is not an essential process of genetic algorithm. The policy of elitism is to include the best individual of every generation into the next generation in order not to lose it due to sampling effects or operator disruption.

Aerodynamic Analysis

Missile DATCOM is an aerodynamic performance tool generated to estimate the control characteristics and aerodynamic stability of missile configurations by employing both empirical and simple aerodynamic theoretical methods. Therefore, Missile DATCOM can be used for the speed regime from subsonic to hypersonic flight. In this study, Missile DATCOM software tool is used for the aerodynamic performance calculations both for its accuracy and relatively short computational time.

Missile DATCOM, as an aerodynamic performance prediction tool, requires the flight conditions and the missile geometry to perform the aerodynamic analysis. . In this design study, the angle of attack is defined between 0° and 10°, and the Mach number is given between the range of 0.1 and 1.2 sternly with guided munitions flight regime.

Outer geometry of a missile can be defined with some specific geometrical parameters. These parameters are shown in **Figure 7**.

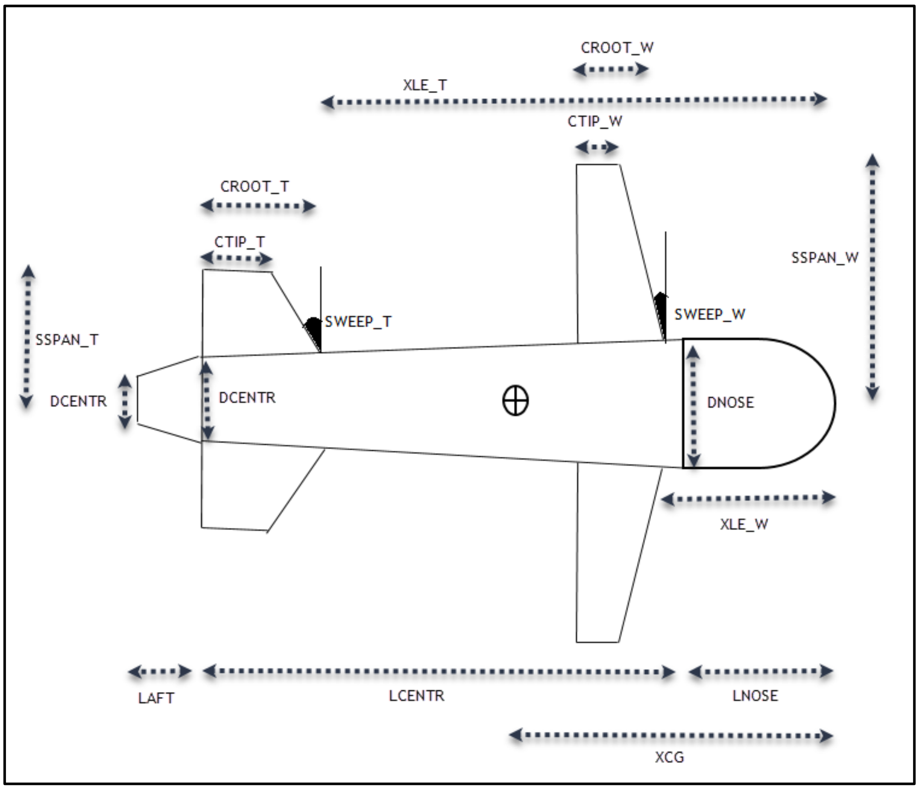

Figure 7. Missile Body External Geometry

RESULTS

A generic 250 lb. Guided munition optimization is chosen as case study. As a first step the limits of the external geometry parameters are decided by constructing a competitor study. These external limits can be divided into four groups as the body parameters, wing parameters, strake parameters and tail parameters.

After specifying the limits 1000 designs, 20 generations with 50 solutions in each generation, are created and evaluated with respect to the selected objectives and constraints**.**

For all the created feasible and unfeasible designs, scatter chart of $C_{L_{\max\_usable}}$ with respect to $(C_L/C_D)_{@trim}$ is given in Figure 8. As there were many constraints, the unfeasible designs are more than the feasible solutions as expected.

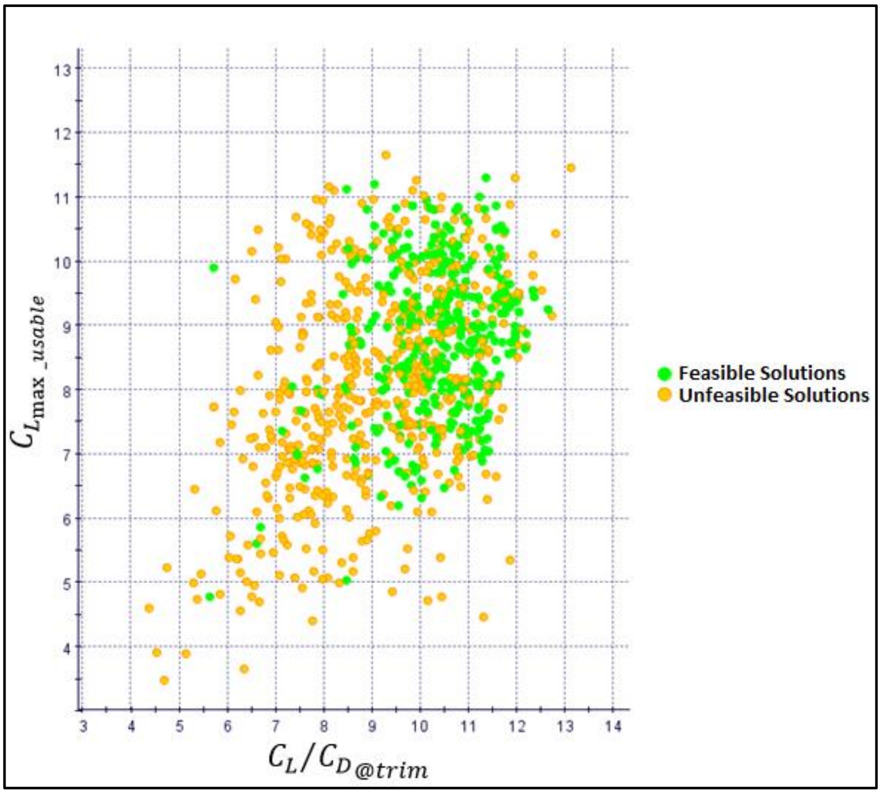

Figure 8. Scatter Chart: $(C_L/C_D)_{@trim}$ vs $C_{L_{\max\_usable}}$

The pareto optimal solutions of this coupled optimization trial and the geometries of the optimum solutions are shown in Figure 9. The numerical values of objective functions of pareto optimal solutions are given in Table 1.

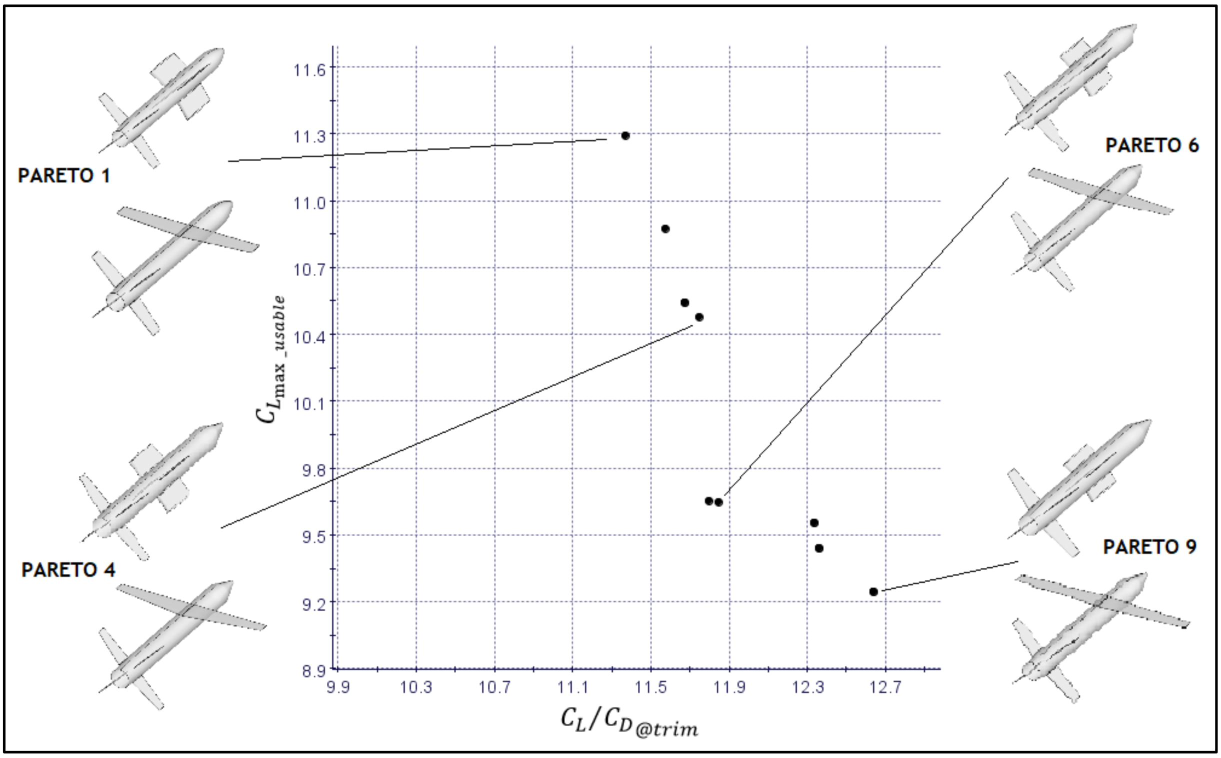

Figure 9. Pareto Optimal Solution (9 Designs)

Table 1. Numerical Values of Objective Functions of Pareto Optimal Solutions

OPTIMAL SOLUTIONS	OBJ 1 $(C_L/C_{D\ @trim})$	OBJ 2$(C_{L_{\max_usable}})$
Pareto 1	11.367	11.291
Pareto 2	11.573	10.874
Pareto 3	11.671	10.545
Pareto 4	11.745	10.480
Pareto 5	11.793	9.654
Pareto 6	11.844	9.649
Pareto 7	12.335	9.556
Pareto 8	12.358	9.442
Pareto 9	12.634	9.247

Optimizing the outer geometry of the missile that can be used both with strakes and wings may limit the capabilities of either version. In the 2nd trial, a classical multi-objective optimization is constituted for a gliding missile with wings and the results are compared with the two version optimization carried out in the 1st optimization trial. As in the previous trials, genetic algorithm is used in the 2nd optimization trial. By keeping the possible variabilities in the optimization procedure such as the optimization algorithm and the objectives as in the 1st optimization trial, the effect of the modular design is studied.

In the 1st optimization is the pareto set is obtained considering pre-determined objective functions. Every solution in pareto set is consist of one version with strakes and one version with wings. In Table 2 the numerical values of lift to drag ratio at trim condition $(C_L/C_D)_{@trim}$ and maximum usable lift coefficient $C_{L_{\max\_usable}}$ of 2nd versions of pareto set obtained in the coupled optimization. Values given have not taken the versions with strakes into account, so the values are different from objective function values given in Table 1.

Table 2. Aerodynamic Parameters of 2nd Version Missiles in Coupled Optimization Pareto Set

OPTIMAL SOLUTIONS	OBJ 1 $(C_L/C_{D\ @trim})$	OBJ 2$(C_{L_{\max_usable}})$
Pareto 1	16.238	21.022
Pareto 2	16.533	21.809
Pareto 3	16.673	20.994
Pareto 4	16.779	20.520
Pareto 5	16.847	21.151
Pareto 6	16.920	20.537
Pareto 7	17.622	21.812
Pareto 8	17.654	21.691
Pareto 9	18.049	21.075

The pareto optimal solutions, in terms of Lift-to-Drag ratio at trim condition $(C_L/C_{D@trim})$ and maximum usable lift coefficient $(C_{L_{\max\_usable}})$, of classical single version optimization trial are given in TABLE and shown in Figure 10.

Table 3. Numerical Values of Objectives for Single Version Optimization

OPTIMAL SOLUTIONS	OBJ 1 $\left(C_L/C_{D\ @trim}\right)$	OBJ 2$\left(C_{L_{\max_usable}}\right)$
Pareto 1	**19.634**	**21.520**
Pareto 2	**19.069**	**26.513**
Pareto 3	**17.682**	**26.911**

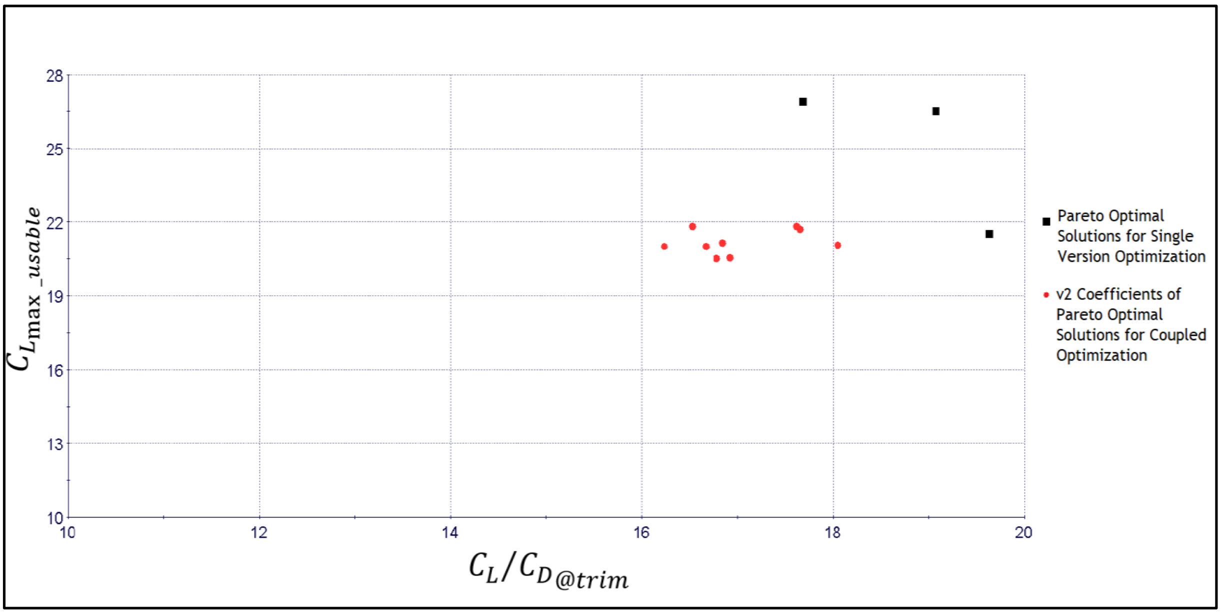

Figure 10. Pareto Optimal Solutions for Single Version Optimization and 2nd Version Missile's Coefficients in Coupled Optimization Pareto Set

CONCLUSION

At the end of the study, a design tool, which enables the user to design a guided missile's outer geometry with and without wings that can fulfill different missions, will be created. When comparing the fixed missile design with the modular missile design, since the modularity increases to the number of constraints, the values of objective functions are observed to be decreased. However, for the selected test case, 250 lb. guided munition, this decrease is not drastic. Even so, this modularity effect shall be investigated further for every missile in subject.

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