Aerodynamic Shape Optimization System for Range Maximization of a Canard-Controlled Missile Using Trajectory-Dependent Aerodynamic Coefficients

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This paper describes a shape optimization study to maximize the range of a guided missile. In order to design a guided missile having maximum range, a shape optimization system is incorporated with a trajectory analysis program and an optimization technique. In particular, trajectory-dependent aerodynamic coefficients are fully considered. In the trajectory analysis step, a component build-up method is directly connected to the equation of motion to calculate aerodynamic coefficients at every time step. In the optimization step, a real coded adaptive range genetic algorithm is adopted to determine the optimal shape of the global maximum range. The shape optimization system of a guided missile can maximize the range of the missile and yield the optimal shapes of canards and tailfins. Finally, the effects of trajectory-dependent aerodynamic coefficients, guidance and control on the range of a missile are illustrated.

Nomenclature

α = angle of attack, rad

δ_c = canards deflection angle, rad

C_A = axial force coefficient

C_L/C_D = lift to drag ratio

C_M = pitching moment coefficient

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C_N = normal force coefficient

h = altitude, m

M = Mach number

SM = static margin

I. Introduction

The typical conceptual design process for missiles is an iterative process, requiring a number of design iterations to achieve balanced emphasis from the diverse inputs and outputs. Figure 1 shows the representative iterative process used for conceptual design synthesis. Based on mission requirements, an initial baseline from an existing missile with a similar mission is established. This baseline is used as a starting point to expedite the missile design convergence. The new conceptual design is evaluated against its flight performance requirements. If the design does not meet the requirements, it is changed and resized for the next iteration and evaluation. If the new missile design meets the requirements, the design is finalized [1].

This series of iterative steps is repeated and the design of each subsystem (aerodynamics, propulsion, weight, and trajectory) also involves a similar series of iterative steps. Typically, the entire process of the missile design requires considerable time and cost. Although a missile design may meet the flight performance and other requirements pertaining to measures of merit and constraints, it nevertheless may not be an optimal missile design [2]. To achieve an optimal missile design, researchers have developed optimization techniques, and research is actively being conducted on possible optimization methods for each area involved in missile design [3-10]. For many years, researchers have applied gradient-based optimization schemes to aerodynamic shape optimization [3-4]. Also, there has been growing interest in the use of global optimization methods in a wide range of design problems, as well as aerodynamic shape optimization. Hybrid optimization methods based on genetic and gradient search algorithms have been applied to three-dimensional shape optimization of ogive-shapes, star-shapes, spiked projectiles and lifting bodies in a hypersonic flow [5]. Anderson et al. [6] applied Pareto genetic algorithms to the multi-objective optimization of missile aerodynamic shape design. Tekinalp and Bingol [7] have developed a simulated annealing method for missile trajectory optimization. Al-Garni et al. [8] presented a fast and reliable technique for aerodynamic shape optimization of supersonic missiles using a Monte-Carlo optimization method. Through the optimization studies undertaken by previous researchers, it has become possible to design guided missiles more efficiently.

However, in the case of aerial vehicles such as ground-to-ground missiles, shape optimization has proved difficult due to such aerodynamic characteristics as rapid changes in the Mach and Reynolds numbers. Ground-to-ground missiles primarily use solid fuel; hence, velocity and altitude change rapidly after launch, resulting in correspondingly rapid changes in the Mach and Reynolds numbers. The Mach and Reynolds numbers are the most important variables determining the aerodynamic characteristics of guided missiles. As such, their rapid variation makes it difficult to predict the missile's aerodynamic characteristics. In shape optimization for guided missiles, the Mach number and the Reynolds number are particularly important determinants of aerodynamic characteristics [11-15]. For this reason, optimizing the external shape of aerial vehicles such as ground-to-ground missiles brings about the problem of having to derive a shape that takes the entire range of flight into account. In this case, repeated calculations of trajectory-dependent aerodynamic coefficients are required. However, a simpler approach in which one-time calculation of optimization defined at a particular flight condition has been employed in the past. In this simpler approach, the effects of guidance and control, as well as the Mach and Reynolds numbers, cannot be described fully. To remove this weakness, full consideration of trajectory-dependent aerodynamic coefficients in missile aerodynamic shape optimization is made in the present study. By doing so, the effects of trajectory-dependent aerodynamic coefficients, guidance and control on the range of a missile are illustrated.

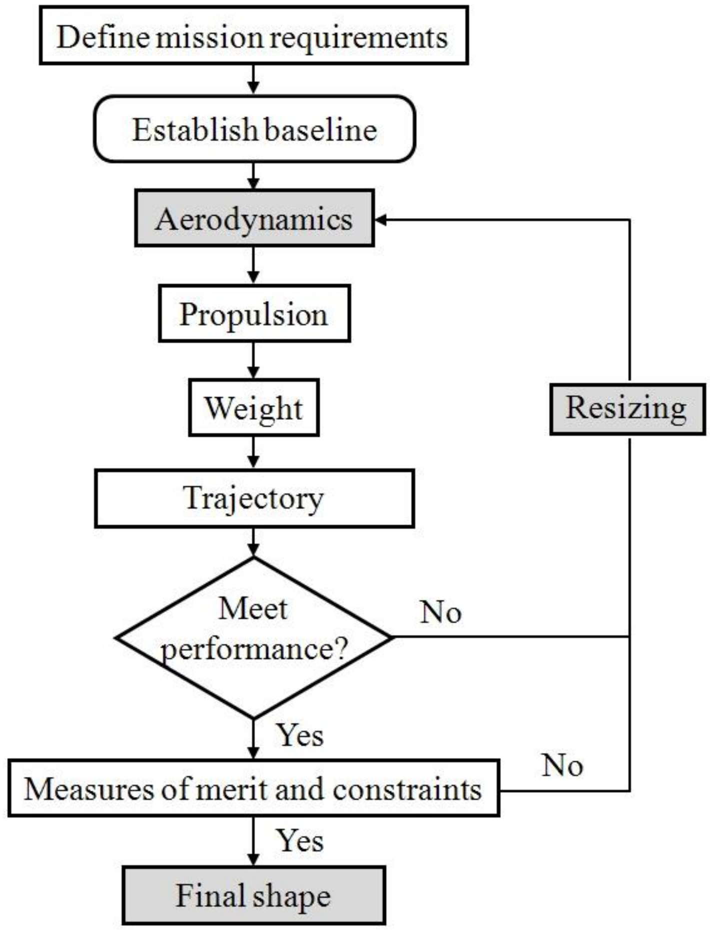


Fig. 1 Flow chart of missile design [1].

II. Aerodynamic Shape Optimization System

This study addresses the issue of aerodynamic shape optimization for maximizing the range of ground-to-ground missiles, such as the U.S. Army's M270 Guided Multiple Launch Rocket System (GMLRS). As shown in Fig. 2, a ground-to-ground missile engages in unguided ballistic flight during the climb phase to extend its range; then, once attaining its apogee point, it begins gliding using pitch-up guidance and control in order to maximize its range. In order to extend the range of such a projectile, it is necessary to minimize drag during the climb so as to increase the maximum speed at the point of highest altitude (apogee), and maximize the lift/drag ratio during descent to maximize the gliding distance, as expressed in Eq. (1).

$$\text{Gliding distance} = \text{Gliding altitude } (h) \times \text{Glide ratio } (C_L/C_D) \quad (1)$$

To achieve the range maximization described above, the repeated calculations of trajectory-dependent aerodynamic coefficients are required in principle. In order to reduce the computational cost, a simpler approach entailing one-time calculation of aerodynamic coefficients defined at a particular flight condition is employed in the past. In this study, full consideration of trajectory-dependent aerodynamic coefficients is made for the purpose of identifying the effects of trajectory-dependent aerodynamic coefficients, guidance and control on the range of a missile. For the determination of aerodynamic coefficients, the component build-up aerodynamic analysis software Missile DATCOM [16, 17] was used to design a flight trajectory analysis program. This program was then linked with a real-coded Adaptive Range Genetic Algorithm (ARGA) [18], a method employed for global optimization, in order to develop a shape optimization system that is capable of range maximization.

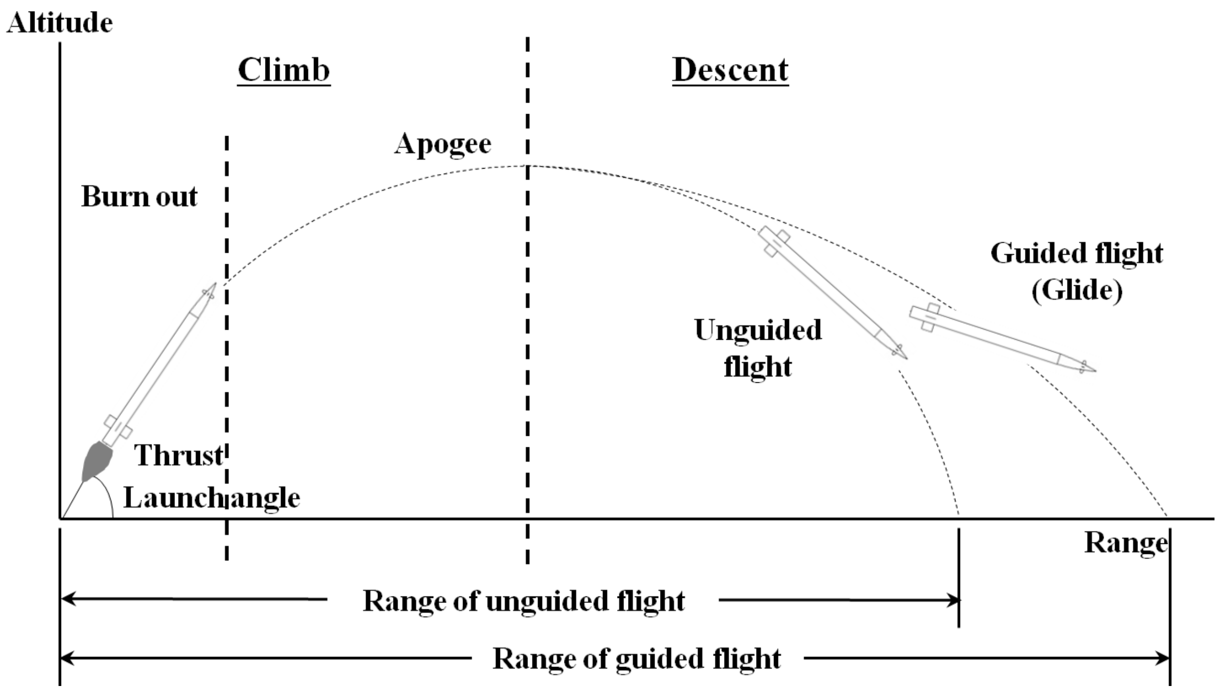


Fig. 2 Trajectory of a guided missile.

A. Trajectory Analysis Program Using Time-Dependent Aerodynamic Coefficients

The flight trajectory analysis program is composed of two parts: the equation of motion and an aerodynamic analysis. The equation of motion part uses factors including flight conditions, the attitude of the aerial vehicle, and the operating force and moment to calculate the motion of the aerial vehicle, and conveys the resulting flight conditions and attitude to the aerodynamic analysis part. The aerodynamic analysis part uses the calculated flight conditions and attitude to perform an aerodynamic analysis, thus determining the force and moment operating on the aerial vehicle, and then conveys the results to the equation of motion part. When a missile flies at high altitude, the short period eigenmotion has low damping. To compensate for this, a stability augmentation system as illustrated in Fig. 3 was adopted to increase dynamic stability during pitch-up guided flight in this study. In the figure, δ_c, Q, K represent the canard deflection angle for pitch-up control, the angular velocity of Y axis, and the gain value of Q, respectively.

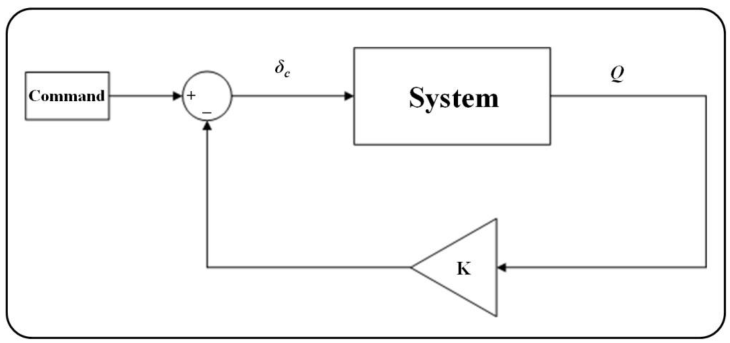


Fig. 3 Stability Augmentation System (SAS).

Using this method, the flight trajectory of the aerial vehicle is calculated at each time step. Hence, the flight trajectory analysis program designed in this study is capable of taking into account changes in the Mach and Reynolds numbers, and can analyze the flight trajectory without building an aerodynamic database [2].

The flight trajectory analysis program developed in this study is based on a three degree-of-freedom model [19] and offers some notable features. First, because the equation of motion is directly linked with the aerodynamic analysis program, Missile DATCOM, it is not necessary to compile an aerodynamic database. Second, it can take into account changes in the Mach and Reynolds numbers resulting not only from velocity variations but also from altitude variations, thus producing flight trajectory analysis results. Therefore, the program developed in this study will be effective for operations that require a large amount of flight trajectory analysis, such as sensitivity analyses and optimization.

An efficient method to calculate the aerodynamic coefficients is vital in the present flight trajectory analysis program. Commonly used aerodynamic analysis methods include wind tunnel testing, computational fluid dynamics, theoretical analysis, and semi-empirical methods combining theory and empirical formulae. For shape optimization, an aerodynamic calculation and flight trajectory analysis must be carried out for arbitrary shapes, necessitating a lengthy time commitment. Therefore, among the analysis methods available, the semi-empirical method, which offers high accuracy in relation to time, was selected and component build-up was chosen as the specific method of analysis. By directly linking the component build-up analysis software and the equation of motion, a flight trajectory analysis program that does not require the generation of an aerodynamic database reflecting changes to the missile's external shape was developed.

The component build-up method of aerodynamics is commonly used in semi-empirical codes. It derives its theoretical basis from the linearized theory where solutions of the equation of motion can be added together in a linear sense. Entire flow-fields are solved simultaneously for all configuration components as opposed to solving for configuration components separately and then combining the results. The configuration has a body, wings, and tails. There are thus several aerodynamic force and moment terms that must be considered separately in the component build-up approach. These include the body alone; the wing alone; the tail alone; the additional force on the body due to the presence of the wings and tails; the additional force on the wings and tails due to the presence of the body; and, finally, the additional force on the tails as a result of being in the downwash field of the wings. Experience has shown that the interference effects between body, wing, and tails on the axial force can be neglected in most cases, except for on the base drag. However, the normal force and pitching moment of the total configuration are affected by all these terms. These aerodynamic components can be summed together to obtain the total aerodynamics [20]. This method offers an advantage of yielding relatively fast and accurate results.

A validation result of the present trajectory code by considering a hydra 70 rocket [21-23] is shown in Fig. 4. As illustrated in the figure, the range prediction of the code is in close agreement with the data obtained by a flight test.

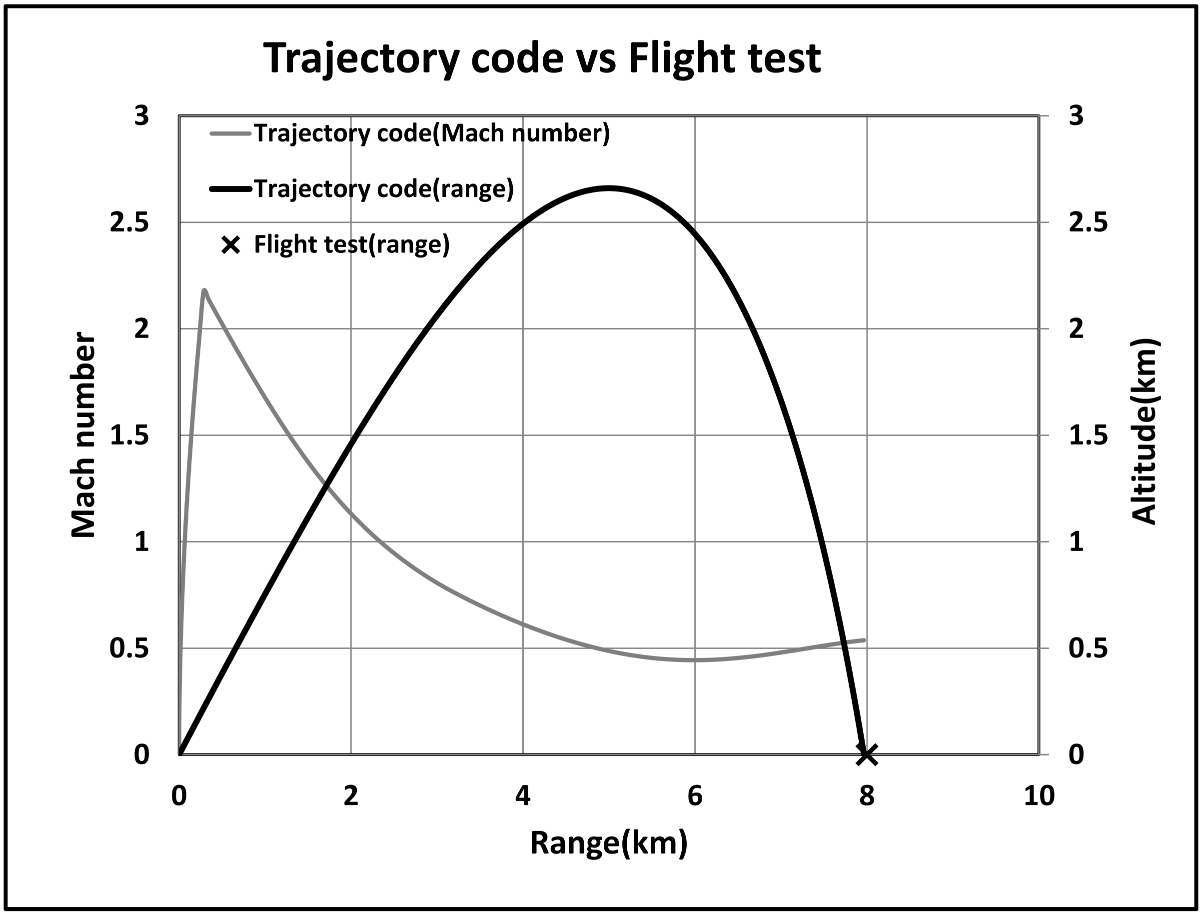
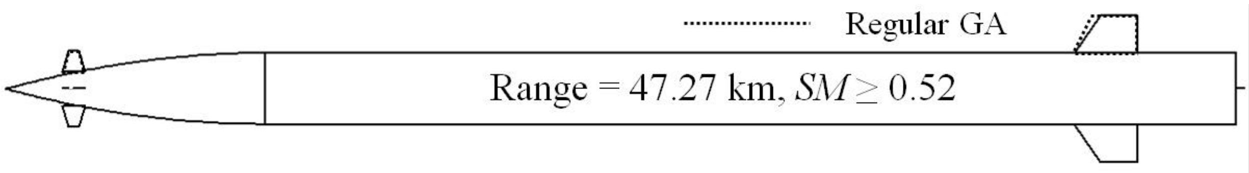


Fig. 4 A validation study of the present trajectory code.

B. Real-Coded Adaptive Range Genetic Algorithm

Among the various existing optimization methods, the real-coded adaptive range genetic algorithm (ARGA) was selected, because it enables global optimization and is more effective than regular genetic algorithms (GA). The basic concept of ARGAs, an approach first proposed by Arakawa and Hagiwara [24], is to use a normal distribution to adapt the population to the range of possibility during optimization. The main difference between ARGA and conventional GA is the introduction of the range adaptation. The essence of ARGAs is to adapt the population toward promising regions during the optimization process, which enables efficient and robust search in good precision while keeping the string length small. Moreover, ARGAs eliminate a need of prior definition of search boundaries since ARGAs distribute solution candidates according to the normal distributions of the design variables in the present population. The advantage of the real-coded ARGA over the regular GA is demonstrated in Fig. 5.



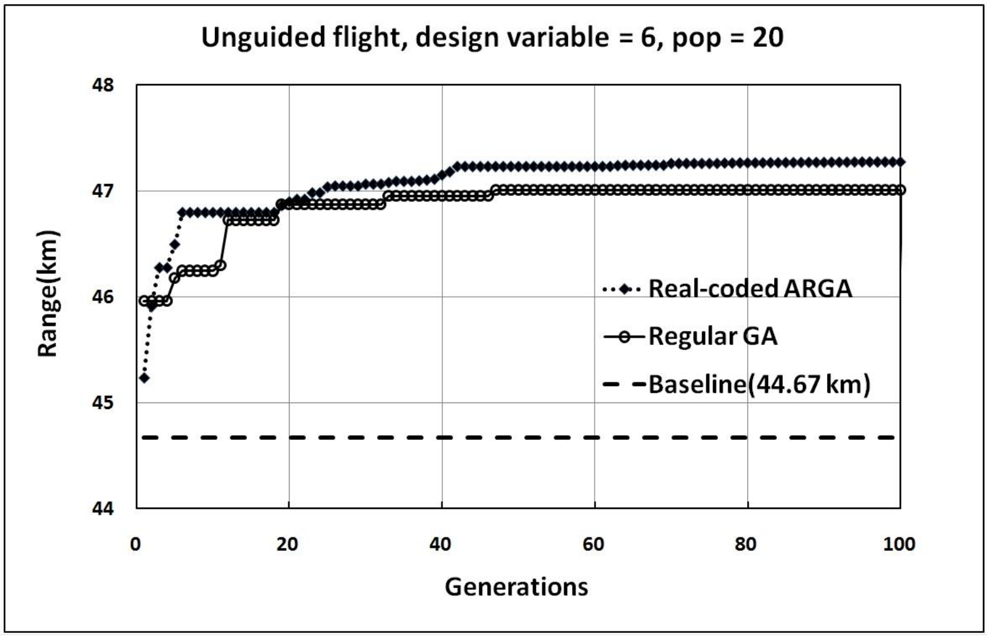


Fig. 5 Real-coded ARGA vs. regular GA.

This method runs counter to the probabilistic mechanism of genetic algorithms, and also eliminates the pre-defined boundary conditions, because its design variables follow a normal distribution. These drawbacks were redressed in an alternative proposed by Oyama, Obayashi, and Nakamura known as the real-coded ARGA [18]. This modified method still uses a normal distribution to select the population for the next generation, with the exception that it also uses the integral of the normal distribution function corresponding to a randomly generated number. This differentiates the real-coded method from binary-coded ARGAs, for which the next generation is set at regular intervals in the normal distribution. The real-coded method also coincides with the probabilistic methodology of existing GAs. Thus, it offers the dual advantages of a reduced search range and the use of a probabilistic method.

The procedure of the real-coded ARGA used in this study is shown in Fig. 6. At every Nth generation, the next generation is created by using the average and standard deviation to determine a new range. The remainder of the procedure is identical to the existing GA method. The letter N denotes the value defined by the user to form an adaptive range from among the overall number of generations. Hence, if N is 3, the adaptive range is formed from the 3rd, 6th, 9th, etc. generations. For this real-coded ARGA, random numbers are generated to form the succeeding generations using a probabilistic method.

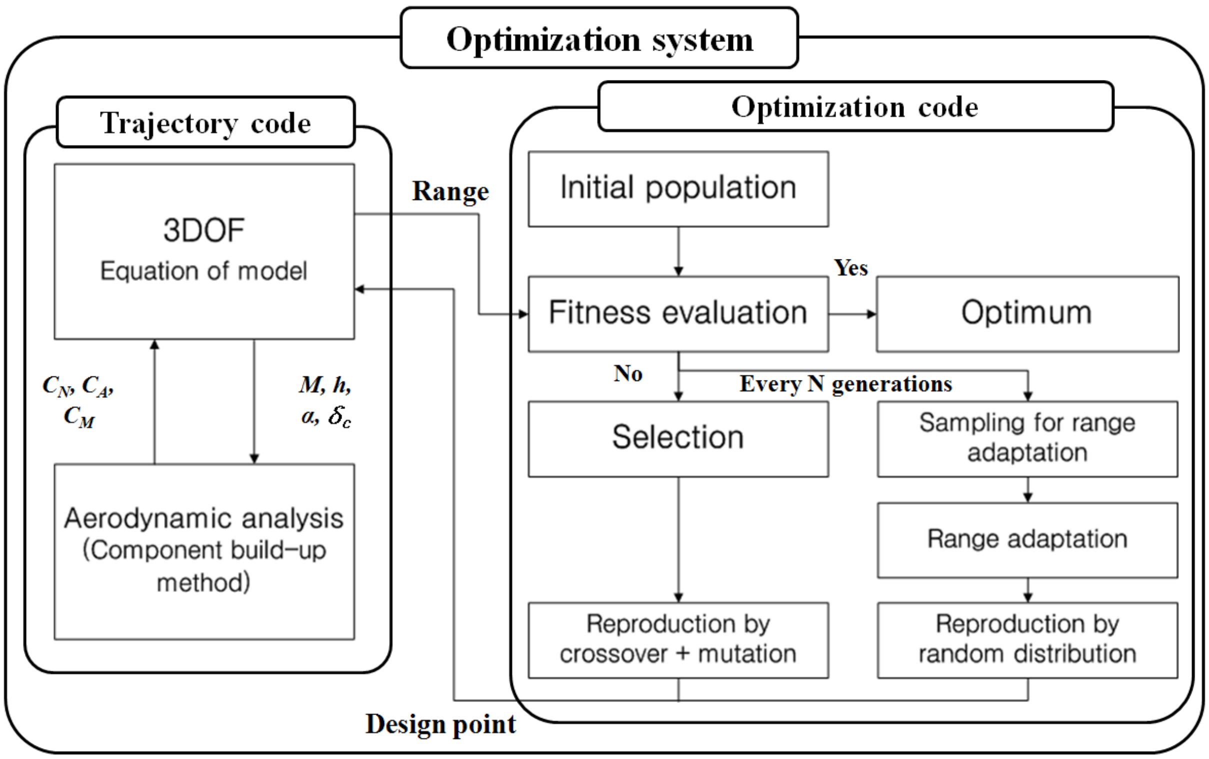


Fig. 6 Range maximization system for a guided missile.

In the real-coded ARGAs, the real value of i-th design variable P_i is encoded to a real number r_i defined in (0,1) so that r_i is equal to the integrations of the normal distribution form $-\infty$ to pn_i,

$$r_i = \int_{-\infty}^{pn_i} N(0,1)(z)dz, \quad P_i = \sigma_i \cdot pn_i + \mu_i, \tag{2}$$

where the average μ_i and the standard deviation σ_i of i-th design variable are calculated by sampling the top half of the previous population to promote the population toward search regions of high fitness. A real string r_i is decoded to a real parameter value $pn_i(r_i)$. A schematic view of this coding is illustrated in Fig. 7.

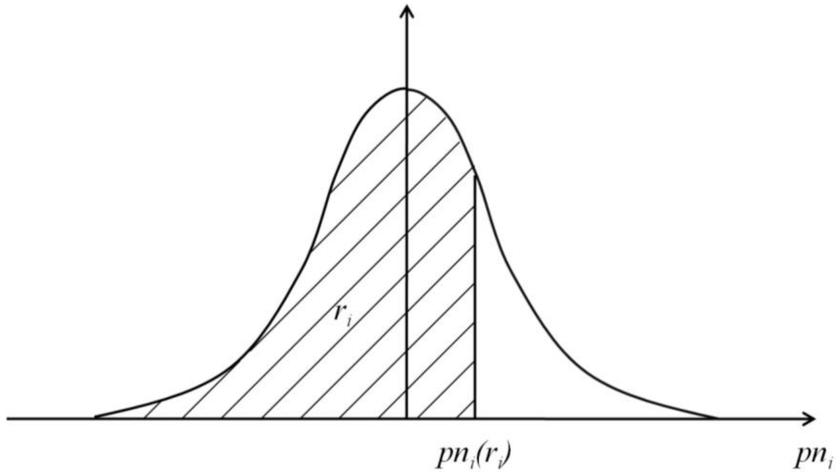


Fig. 7 Decoding for real-coded ARGAs.

In this study, the real-coded ARGA proposed by Oyama, Obayashi, and Nakamura was used to develop the optimization code, which was then linked to the flight trajectory analysis program in order to build a global range maximization system for a guided missile.

C. Optimization System for the Range Maximization of a Guided Missile

Using the abovementioned trajectory analysis program and the optimization method based on real-coded ARGA, a shape optimization system for a guided missile was developed, as shown in Fig. 6. Once the design variables and design range have been set, design points are selected from the real-coded ARGA and conveyed to the flight trajectory analysis program. At this point, the trajectory analysis program generates input for the conveyed design points to analyze the flight trajectory, and conveys the corresponding range back to the ARGA. Based on the computed range, the real-coded ARGA constitutes the next-generation design points for range maximization, and repeats the abovementioned steps. The guided missile's optimal shape is derived through this iterative process.

III. Case Study: Application to a Canard-Controlled Missile

The developed optimization system was used to maximize the range of a canard controlled missile. Detailed information of the baseline was given in Fig. 8 [25-27]. The baseline consisted of a cylindrical body with trapezoidal canards and rectangular tailfins, and a tangent ogive nose with a fineness ratio of 4. The body measured 22.49 cm in diameter and 390.13 cm in length. The canards and tailfins were arranged in a × and + form, respectively. All four canards were used during the pitch-up guidance and control phase with a maximum deflection angle of 15˚.

Thickness ratios and sweep-back angles of canards and tailfins are summarized in table 1. The total weight was 308 kg, the weight after combustion was 191 kg, the thrust was 62,275 kg·m/s^2 for 4.5 seconds of combustion, and I_{yy} was 382 kg·m^2. The launch angle was 45˚ and minimum static margin of baseline was 2.0 with respect to the body diameter. For this baseline, the range of unguided flight was calculated as 44.67 km, and the range of guided flight was calculated as 59.83 km. Range maximization was performed both for unguided flight and guided flight starting from the apogee point.

Table 1 Thickness ratios and sweep-back angles of canards and tailfins.

Baseline	Thickness ratio	Sweep-back angle (deg)
Canard	0.05	14.41
Tailfin	0.05	0

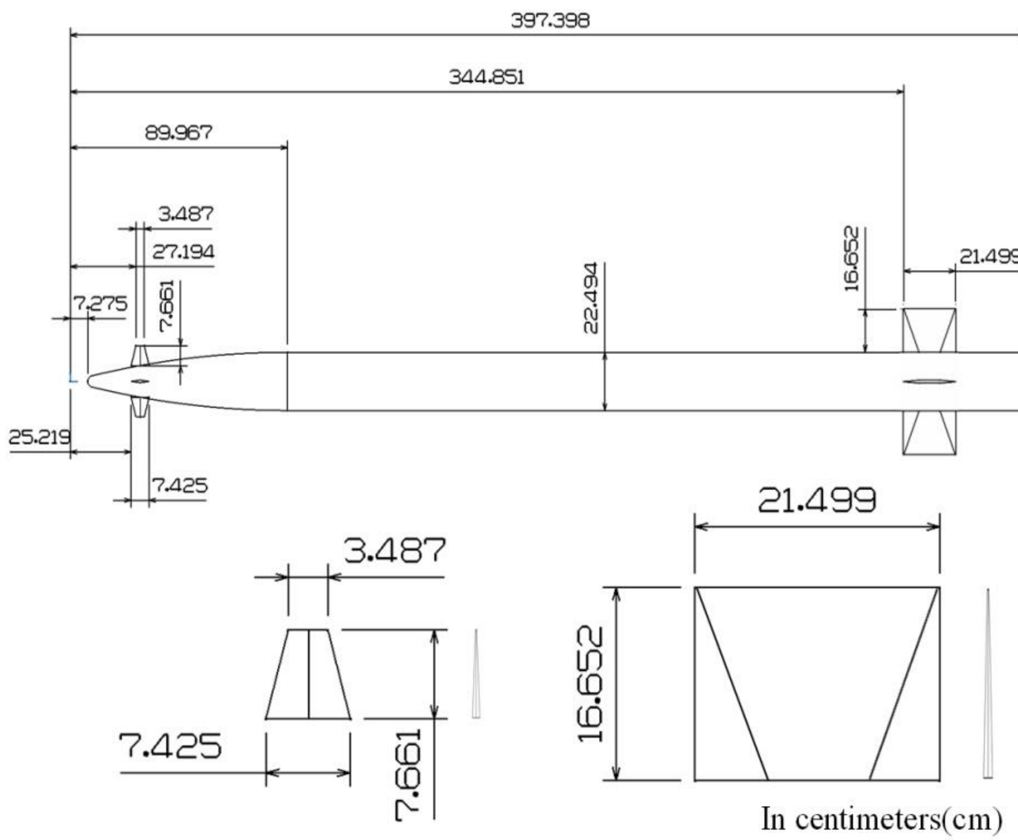


Fig. 8 Baseline.

A. Formulation of the Optimization Problem

Objective function: Range maximization

Design variables: Shape variables for canards and tailfins

Constraint: *Static Margin(SM)* ≥ 0.5

As seen in Fig. 9, an optimization problem was formulated for a canard guided missile, and shape optimization was performed to maximize the missile's range. The objective function was range maximization, and the design variables were six external shape variables that are decisive in shaping the canards and tailfins: the root chord, tip chord, and the span for the canards and tailfins, respectively. The area and sweep-back angle for the canards and tailfins were determined by a combination of several variables. The ranges for these variables are shown in Fig. 9 and Table 2. The canard was designed to be symmetrical about the actuator axis in order to minimize the hinge moment operating on the actuator. For the tailfin, the design range was set to maximize the longitudinal stability while reducing the area. The design range for the variables was arranged such that a case would not occur wherein the tip chord of the canard and tailfin became longer than the root chord, resulting in a sweep-forward angle. The weight and the center of gravity of the missile are kept constant during the optimal design.

The constraint involved was to secure the longitudinal stability. Therefore, to maintain the static margin (*SM*) during flight, it was set to be equal to or above 0.5 ($SM \geq 0.5$). Accordingly, when optimization using the real-coded ARGA resulted in a static margin less than 0.5 ($SM < 0.5$), a penalty function was applied as follows:

$$\text{Maximize } F_i = f_i(X) - P_i(X) \tag{3}$$

In Eq. (3), F_i signifies the fitness of the ith design, $f_i(X)$ the objective function value of the ith design, and $P_i(X)$ the penalty function for the ith design. $P_i(X)$ is a constraining function; when there is a sufficient static margin, $P_i(X)$ equals 0, but if there is no static margin, the value of $P_i(X)$ is substantially greater than the objective function value (e.g. $P_i(X)$ =100). In this manner, the fitness value was designed to be reduced if the individual design in question exceeded the given constraints, thus lessening the probability of it being included in the next generation. For the process of shape optimization, the number of generations was set at 100, and the population per generation was set at 20.

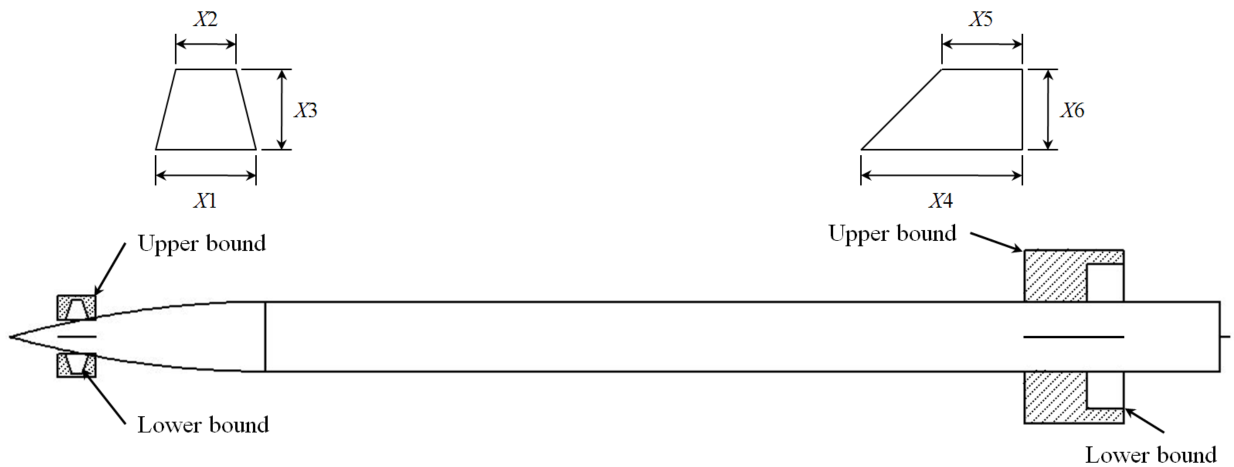


Fig. 9 Design variables and design range.

Table 2 Summary of design variables and range.

Canard	Lower bound (cm)	Upper bound (cm)
Root chord (*X*1)	7.42	12.00
Tip chord (*X*2)	3.49	12.00
Span (*X*3)	6.40	7.66

Tailfin	Lower bound (cm)	Upper bound (cm)
Root chord (*X*4)	12.00	32.00
Tip chord (*X*5)	12.00	32.00
Span (*X*6)	12.00	16.65

B. Range Maximization for Unguided Flight

Range maximization for unguided flight involves maximizing the missile's ground-to-ground flight distance from the firing point to the landing point when there is no guidance or control for the extended range during the flight. Accordingly, to achieve maximum range for unguided flight, the projectile must be designed to minimize drag for the entire flight; in other words, the canard and tailfin must be shaped such that drag is minimized throughout the flight. Therefore, the optimal shape for unguided flight will likely be one that has the smallest possible area and a sweep-back angle that minimizes wave drag.

Table 3 shows the optimal shape for unguided range maximization derived in this study. As expected, the canard assumed a shape that minimizes drag, while the tailfin took a shape that minimizes drag while maintaining the required static margin. This new shape extended the range of the baseline by approximately 5.83%. Figure 10 shows that the change in range converges at around the 50th generation.

For extending the range of an unguided missile, the simpler approach minimized the drag coefficient at specific flight conditions such as Mach number 1.6 and sea level. On the other hand, the effects of the dependence of the Mach and Reynolds numbers of aerodynamic coefficients on the range of a missile are fully taken into account in the present work. Figure 11 and Table 4 show the extension of the range for unguided flight and the improvement over the conventional specific condition based optimization. In addition, it may be noted from these results that the critical effects associated with the dependence of the Mach and Reynolds numbers of aerodynamic coefficients begin to appear near the apogee point mainly due to large variation of the density.

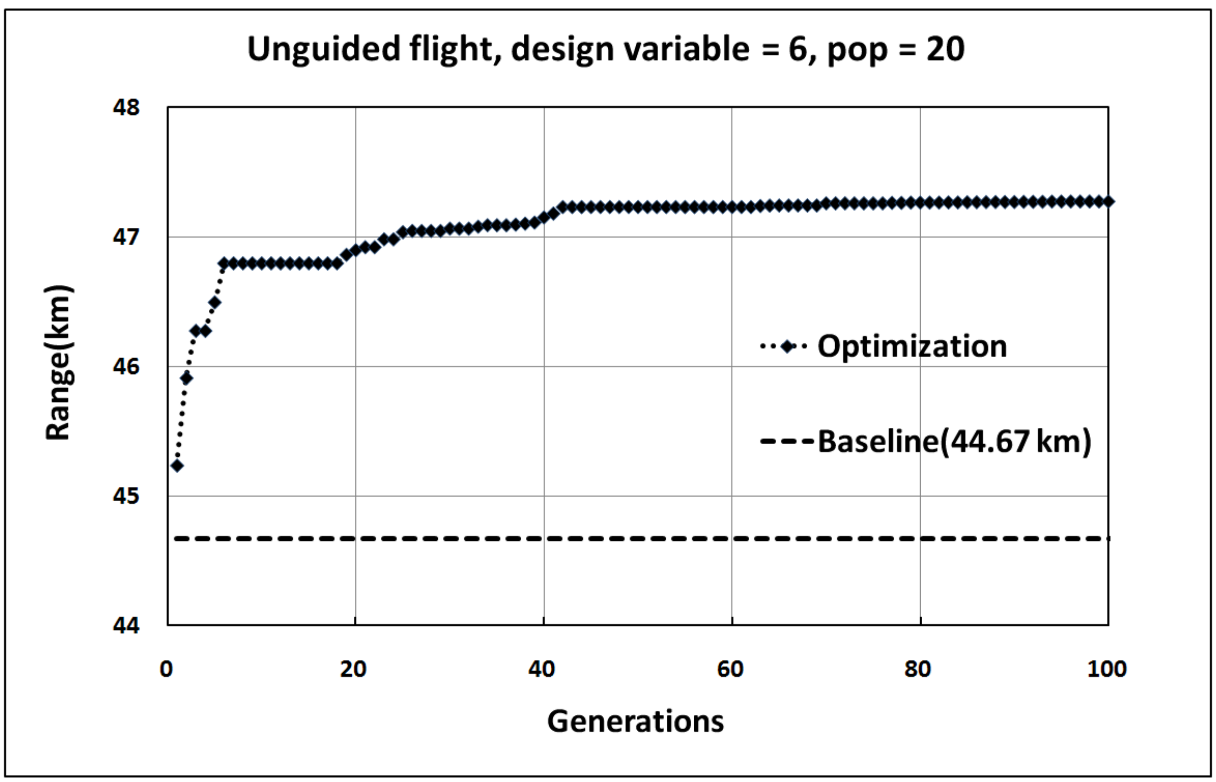
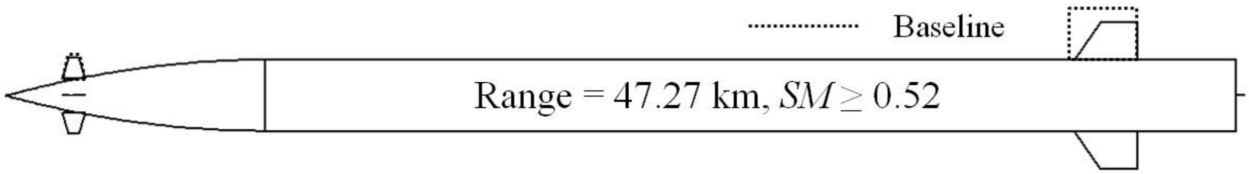


Fig. 10 Range convergence history of unguided flight.

Table 3 Optimal shape results for unguided flight.



Unguided flight optimization	Baseline	Optimal shape	Range extension
Range (km)	44.67	47.27	5.83 (%)

Optimal shape	Canard	Tailfin
Root chord (cm)	7.42	20.24
Tip chord (cm)	3.49	12.00
Span (cm)	6.43	12.00
Sweep-back angle (deg)	17.00	34.48

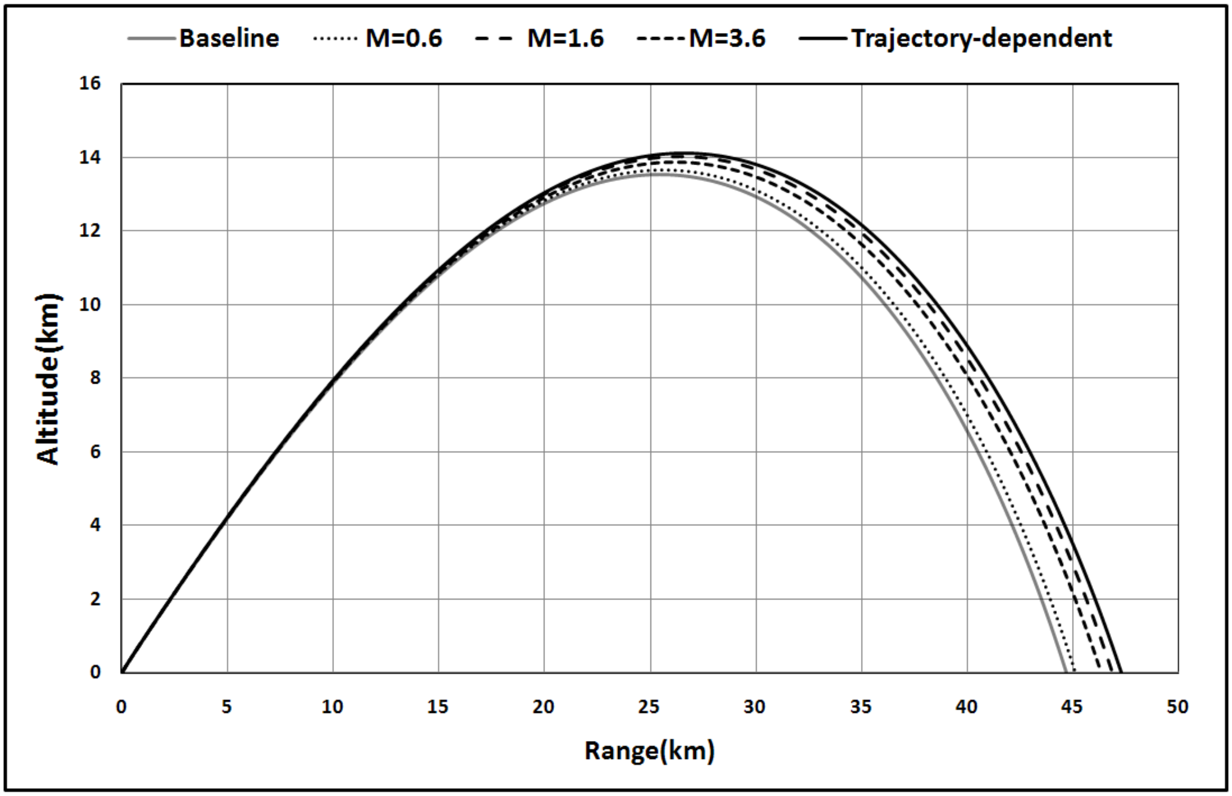
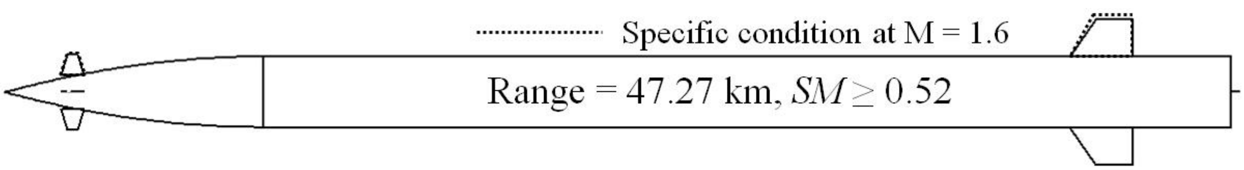


Fig. 11 Optimization results (trajectory-dependent vs. specific condition based optimization).

Table 4 Optimization results (trajectory-dependent vs. specific condition based optimization).



Aerodynamic shape optimization	Range (km)	Range extension (%)
Baseline	44.67	-
M=0.6	45.08	0.93
M=1.6	46.88	4.96
M=3.6	46.33	3.72
Trajectory-dependent	47.27	5.83

C. Range Maximization for Guided Flight

Range maximization for guided flight entails maximization of the distance from the projectile's launch point to beyond the apogee point in the projectile's trajectory, when it begins canard pitch-up control to glide. Thus, the optimal shape will minimize drag during the climbing phase while maximizing the lift/drag ratio during descent. Table 5 shows the optimal shape for guided range maximization obtained in this study. A deflection angle of 15° is applied to all four canards during the pitch-up guidance. The derived shape reduced wave drag during the climbing phase, while increasing the area of the canard to enhance control performance and thus enlarge the trim angle of attack during the gliding phase. The tailfin was also shaped so as to reduce wave drag during the climbing phase and increase the lift/drag ratio during the gliding phase by enlarging the effective area. The new shape extended the range of the baseline by approximately 21.4%. Figure 12, which tracks the change in range for each successive generation, shows that the range converges at around the 30th generation.

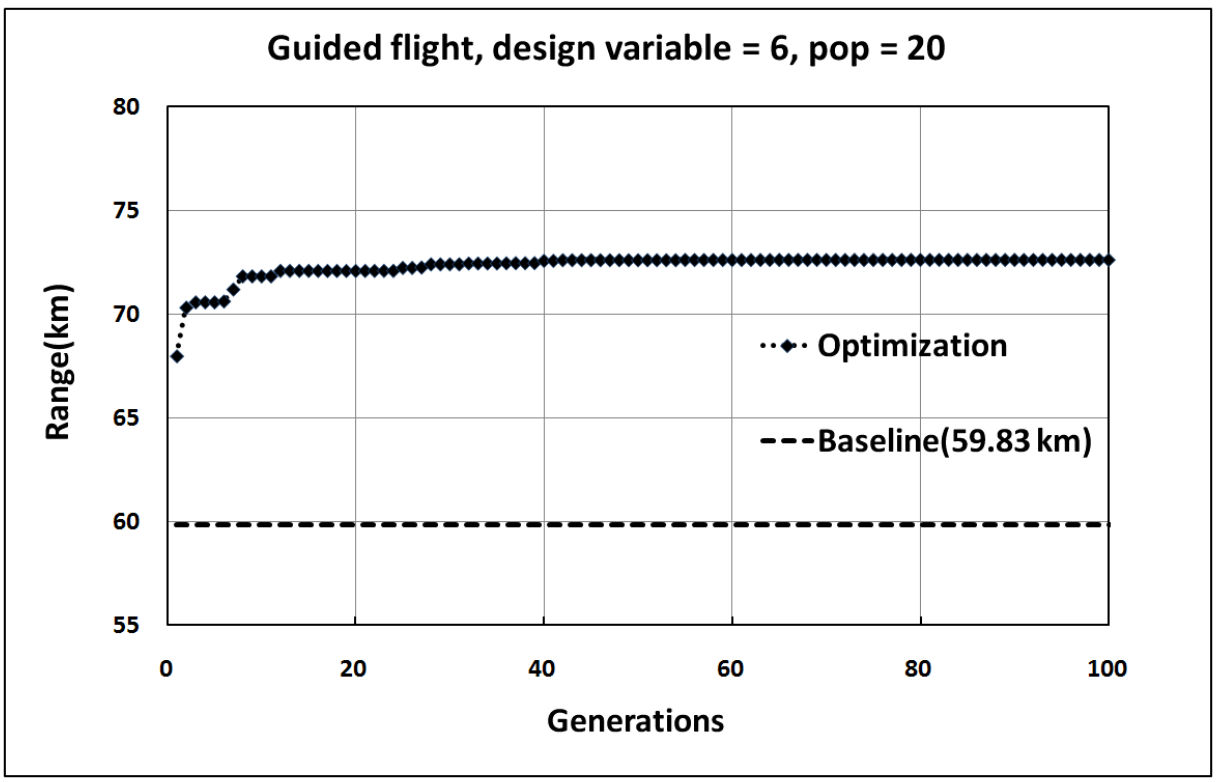
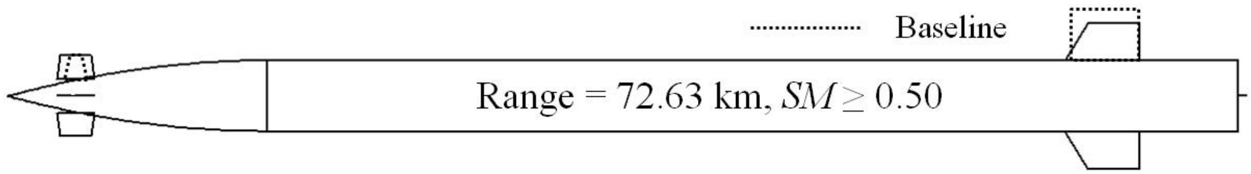


Fig. 12 Range convergence history of guided flight.

Table 5 Optimal shape results for guided flight.



Guided flight optimization	Baseline	Optimal shape	Range extension
Range (km)	59.83	72.63	21.40 (%)

Optimal shape	Canard	Tailfin
Root chord (cm)	11.97	23.67
Tip chord (cm)	9.54	16.63
Span (cm)	7.41	12.01
Sweep-back angle (deg)	9.31	30.38

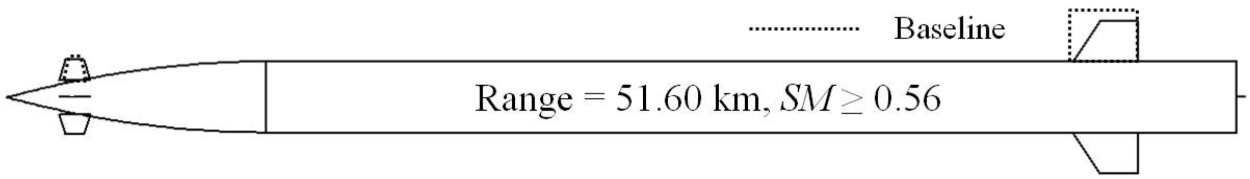
D. Additional Design Variable: Launch Angle

To verify the expandability of the shape optimization system developed in this study, shape optimizations for both unguided and guided flight were repeated with the launch angle added as a design variable that is unrelated to the missile's shape. The range of the launch angle was set between 40˚ and 70˚, with the shape design variables and ranges for the canard and the tailfin retained as given above.

Table 6 shows the optimization results of the range maximization for unguided flight with the launch angle added as a design variable. The optimal launch angle was 56.58˚, with the resulting trajectory and shape expected to maximize the drag reduction caused by the effect of gravity and the increase in dynamic pressure during high-altitude flight. Figure 13 illustrates the changes in the missile's flight trajectory and Mach number with the shape optimized for unguided flight. For a launch angle of 56.58˚, the respective ranges for the baseline and the optimal shape were 44.67 km and 51.60 km, reflecting an increase of 15.51% for the optimized case.

Table 7 shows the optimization results obtained for guided flight for range maximization with the launch angle as an additional design variable. The optimal launch angle was 60.81˚, which has been increased to maximize the gliding effect by enabling high-altitude flight. Figure 14 shows the changes in flight trajectory and Mach number for the optimal shape during guided flight. As can be seen here, the guided range was greatly extended by gliding after the point of highest altitude. The ranges for the baseline and the optimal shape were 59.83 km and 89.90 km, respectively, constituting an extension of approximately 50.27%. The above results confirm that the maximum range is increased by the addition of an appropriate design variable, and verify the expandability of the optimization system developed in this study.

Table 6 Optimal shape results for unguided flight (additional design variable: launch angle).



Unguided optimization	Baseline	Optimal shape	Range extension
Range (km)	44.67	51.60	15.51 (%)
Launch angle (deg)	45.00	56.58	

Optimal shape	Canard	Tailfin
Root chord (cm)	9.85	20.89
Tip chord (cm)	6.02	12.14
Span (cm)	6.42	12.96
Sweep-back angle (deg)	16.61	34.03

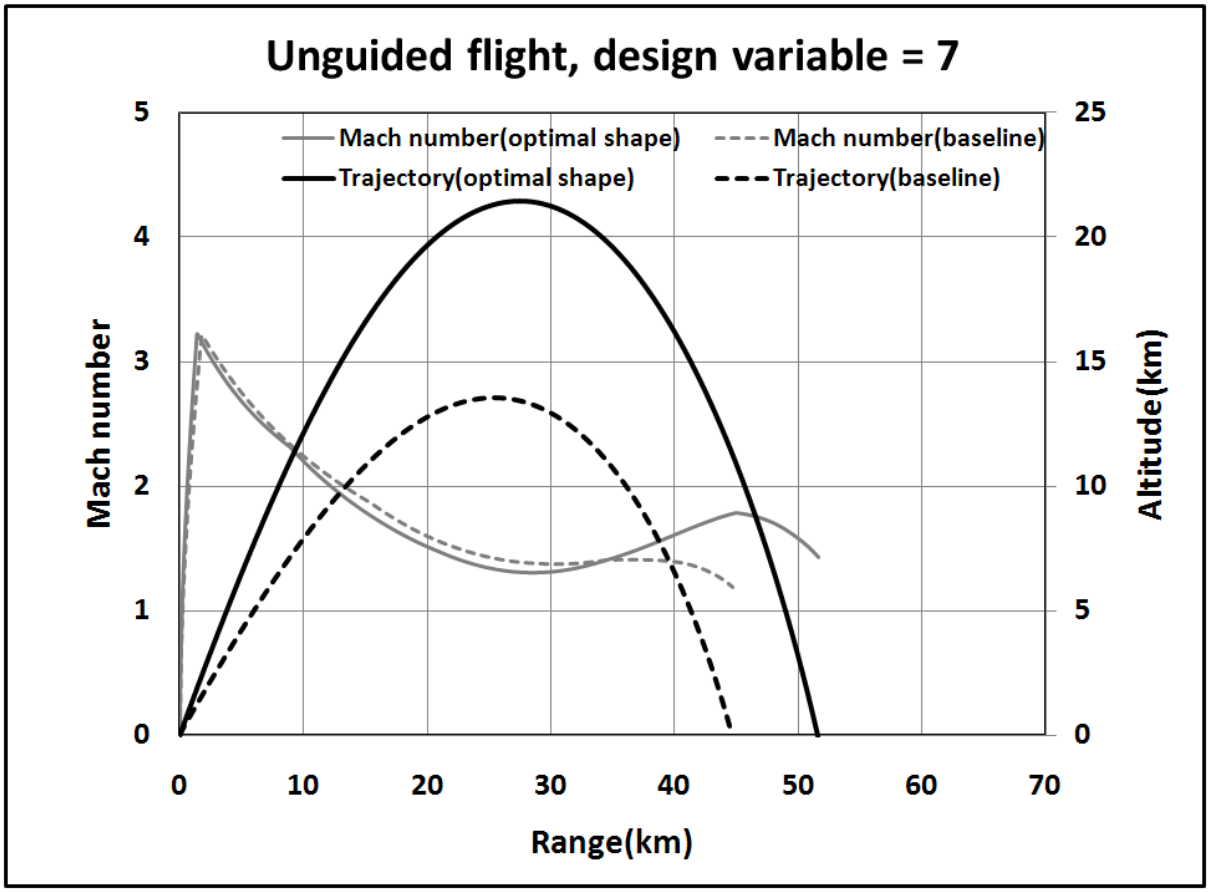
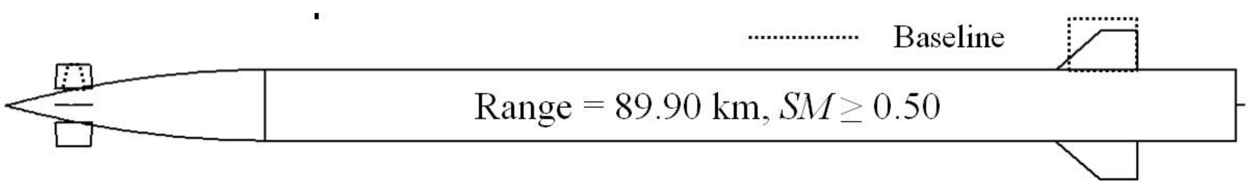


Fig. 13 Trajectory of unguided flight (additional design variable: launch angle).

Table 7 Optimal shape results for guided flight (additional design variable: launch angle).



Unguided optimization	Baseline	Optimal shape	Range extension
Range (km)	59.83	89.90	50.27 (%)
Launch angle (deg)	45.00	60.81	

Optimal shape	Canard	Tailfin
Root chord (cm)	11.70	26.22
Tip chord (cm)	10.54	12.00
Span (cm)	7.54	12.41
Sweep-back angle (deg)	4.40	48.89

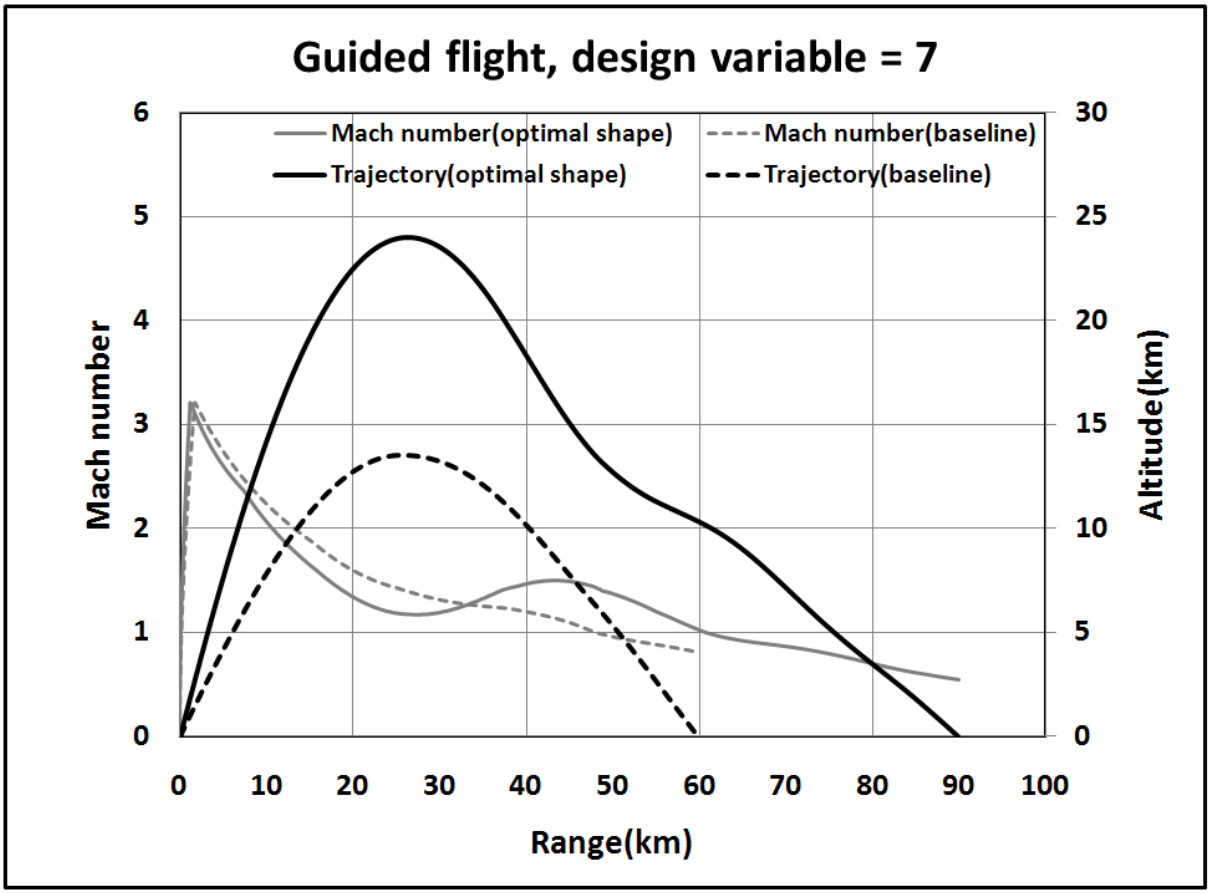


Fig. 14 Trajectory of guided flight (additional design variable: launch angle).

IV. Conclusions

This study conducted an aerodynamic shape optimization in order to achieve maximum range in ground-to-ground missiles. To design a guided missile having maximum range, a shape optimization system is incorporated with a trajectory analysis program and an optimization technique. In the trajectory analysis step, a component build-up method is directly connected to the equation of motion to calculate aerodynamic coefficients at every time step. In this process, the trajectory-dependence property of the aerodynamic coefficients is fully considered. In the optimization step, a real coded ARGA is adopted to determine the optimal shape of the global maximum range. Using the shape optimization system of a guided missile, range maximization was performed for the range of unguided flight and guided flight. In particular, the effects of trajectory-dependent aerodynamic coefficients, guidance and control on the range of the missile are investigated in detail. It was found that the shape optimization system of a guided missile can maximize the range of the missile and can yield the optimal shapes of canards and tailfins. The analysis results confirmed that the optimal shape thus derived extended the range of the baseline by 5.8% for unguided flight and by 21.4% for guided flight.

The aerodynamic analysis program used in this study is a component build-up method, Missile DATCOM. Therefore, the accuracy of the theoretical investigation of the present system will be determined by the accuracy of the method. It thus remains to be seen whether the present theoretical analysis will carry over to the flight test results. Nevertheless, we expect that the qualitative trend in the range associated with guidance and control, and trajectory-dependent aerodynamic coefficients will remain important.

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