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DEVELOPMENT OF AN INTEGRATED PARAMETRIC ENVIRONMENT FOR CONCEPTUAL HYPERSONIC MISSILE SIZING

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Abstract

This paper outlines the method by which a graduate missile design team studying at Georgia Tech's Aerospace System Design Laboratory (ASDL) created an environment that would link design parameters to vehicle metrics for the design of a High Speed Standoff Missile. The sizing and synthesis environment parametrically links multiple physics based disciplinary analyses, so that many aspects of the design can be studied simultaneously. That environment was then used to conceptually design a missile that best met the unobtainable requirements set by the customer. The process resulted in the conceptual design of a liquid fueled ramjet cruise missile that was compatible with the Vertical Launch System. The missile cruised at Mach 5, and was capable of striking targets up to 1462 km away.

Introduction

As the aerospace industry advances, it often becomes impossible to design a vehicle to meet all of the requirements set by the customer simultaneously. Requirements may conflict with one another, forcing the designer to conduct tradeoffs within the design. When it is infeasible to design the vehicle to meet all of the requirements, the designer needs a method to determine which specific requirements the vehicle should be designed to meet. Any such method would require the ability to accurately relate vehicle design variables to the system metrics of interest with a sizing and synthesis environment.

Currently, a commercially available multidisciplinary sizing and synthesis program for the design of missiles is not available in the open literature. Fixed wing aircraft designers have several options, such as FLOPS [1]. These codes incorporate the disciplines traditionally studied in aircraft design, such as aerodynamics and propulsion, with trajectory analysis to size a vehicle. Unfortunately, these programs cannot simply be adapted for missile design because missile characteristics fall outside of the ranges of parameters that these codes are valid for.

The objective of this study was to create an environment that integrates disciplinary codes for the conceptual sizing of a hypersonic missile. The environment was required to be capable of integrating codes that were either commercially available, or written internally. The environment also had to be robust enough to allow for a wide range of design space to be explored. Once such an environment was created the design space could be fully explored. In this case, the design variables consisted of design mission parameters. The exploration of these parameters would allow the designer to fully understand and quantify the tradeoffs between conflicting requirements. Additionally, the automated mapping of mission parameters to vehicle characteristics would allow the designer to optimize the missile design based on weighting of requirements. Finally, the relating of the mission to the design parameters would allow the feasibility of possible missions to be determined. .

This environment is necessary when the performance requirements for the missile are nebulous. A Request for Proposal (RFP), written as a student exercise, served as the basis for customer requirements for the design of a specific hypersonic missile. This paper will describe the application of the proposed parametric missile design environment, and its application to advanced design methods.

Approach

The design approach used was adapted from the generic design methodology developed at the Georgia Tech Aerospace Systems Design Laboratory (ASDL) and is documented in Reference [2]. The methodology has eight steps, but it was modified for this application. The steps are outlined below:

1. Problem Definition
2. Concept Space Definition

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3. Identify Modeling and Simulation Environment
4. Design Space Investigation
5. Determination of Feasibility

The problem definition is required to both ensure that the customer requirements are understood and create a hierarchy of requirements. The requirements were clearly outlined in the RFP, and included the design of a missile that was capable of striking a target between 500 and 1500 km away, within 5 to 15 minutes. The vehicle was required to cruise between Mach 4 and Mach 6, and impact its target at a speed between 2000 and 4000 fps. The range of performance requirements left the designers to determine to what degree to meet each requirement.

The RFP requirements were not given a relative importance. In this phase, it was determined that maximum range and time to target were the most important requirements. Because the time to target was not tied to a distance, another metric, average ground speed was created and given a high priority as well. Impact speed was disregarded for the maximum range mission, and cruise Mach was dropped as a customer requirement because it proved irrelevant when compared to total time to target. A mission planner is only concerned with how long it would take a weapon system to reach its target destination.

During the concept space definition phase, several air-breathing propulsion baselines were examined. They included, in order of increasing complexity: a ducted rocket, a liquid fueled ramjet, a solid fueled ramjet, and a scramjet. After an exhaustive analysis and comparison that is not the focus of this paper, it was determined that the liquid fuel ramjet was the best propulsion system for the HSSM.

The modeling and simulation phase of design was the creation of the integrated environment, and was the most exhaustive portion of the design methodology. In this phase, the disciplinary analyses are examined and selected. If they did not exist, codes were written. Once all of the disciplinary analyses were identified, they were integrated. The identification and integration of codes is described at length in upcoming sections of this paper. The inputs to the environment were the mission parameters and the outputs were vehicle characteristics. Once created, the integrated set of analyses served as a sizing and synthesis environment for the rest of the design phase.

Once the sizing and synthesis environment was created, that design space needed to be explored to determine which mission would be best to design the missile for. Because there are were infinite number of design missions, and the sizing and synthesis environment ran slowly, it was not feasible to run every possible mission through the environment. Instead, a metamodel of the environment was created.

A metamodel is a model of a small segment of a more sophisticated analysis model, based on statistical analysis of design inputs and response metrics. A metamodel uses simple equations to relate independent variables to responses, allowing for a much simpler calculation of the responses. The metamodel used in this study was in the form of a Response Surface Equation (RSE), given in Equation (1).

$$RSE = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j \qquad (1)$$

where

n = number of factors
b_i = regression coefficients for linear terms
b_{ii} = regression coefficients for pure quadratic terms
b_{ij} = regression coefficients for cross product terms
x_i, x_j = design variables or factors

The coefficients that make up the RSE are determined by regressing sample data points taken from the code against the input variables. A pre-determined Design of Experiments (DoE) selected the specific cases of the input variables that were run. A DoE is an orthogonal array that minimizes the number of data points that must be run while still affording enough information to create RSE's. JMP [3], a statistical package, generated a DoE and regressed the corresponding data into RSE's. JMP acts as a pre- and post-processor for constructing RSE's, as well as giving the user the ability to visualize the effects of each design variable on each response. JMP also allows the design variables to be optimized based on relative weightings and targets given to the responses.

The final step employed in this process was the examination of system feasibility. This step was closely intertwined with the design space exploration. First, the feasibility of any design that fits into the ranges of the design space can be easily determined with the metamodel. Second, the constraints on the design space on each response can be visualized two-dimensionally, allowing the designer to see the feasible and infeasible design space. Finally, running thousands of cases generated by a Monte Carlo random number generator allows the user to determine what percentage of the entire design space is feasible.

Creating the Integrated Sizing and Synthesis Environment

The first step in identifying the modeling and simulation environment involved determining the best way to analyze every discipline involved in missile sizing. Because no integrated environment existed, the designers were given the freedom to select the best code available for each discipline. For each discipline, an analysis tool was either selected or created

Disciplinary Analyses

Table I lists the disciplinary analyses along with their respective platform. Note that only the aerodynamics, propulsion, and geometry modeling analyses were conducted using commercially available codes; where as the remaining analyses were conducted by in-house written MATLAB codes.

Table I: List of Disciplinary Analysis Platforms

Analysis	Platform
Inlet Analysis	MATLAB (Windows)
Propulsion	RAMSCRAM (UNIX)
Geometry Modeling	RAM (UNIX)
Aerodynamics	BDAP/AWAVE/SHABP (UNIX)
Trajectory and Sizing	MATLAB (Windows)
Structural Analysis	MATLAB (Windows)
Stability Analysis	MATLAB (Windows)

A brief overview of each disciplinary analysis is included in this section. A complete explanation of the methods used to analyze each discipline is beyond the scope of this paper. As will be discussed in the following section, the main objective of this paper is to introduce the assimilation of these codes into a parametric integrated sizing and synthesis environment.

Inlet

The inlet design analysis consists of an internally developed MATLAB routine that optimizes two-dimensional geometry with three fixed ramps. For a given cruise Mach and nose height (vertical distance between the nose tip and cowl lip), the routine calculates the ramp lengths and angles that allow for each oblique shock to attach to the cowl lip based on a design Mach number. In addition, the effective inlet height, as well as the other geometry illustrated in Figure 1 is calculated.

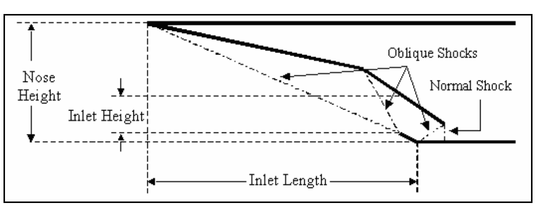

Figure 1: Inlet Analysis Configuration

Propulsion

The propulsion analysis consists of the *RAMSCRAM* FORTRAN analysis code developed by NASA [4]. It was designed for the cycle analysis of hypersonic, air-breathing propulsion systems, including ducted rockets, ramjets, and scramjets. Using efficiencies to account for flow path losses, it calculated 1-D flow properties at each component interface by marching through the engine flow path. The engine flow path consists of the external ramps of the inlet, the internal compression section from the cowl lip to the internal normal shock, the diffuser, the combustor, the nozzle convergent section, and the nozzle divergent section.

RAMSCRAM uses equilibrium thermodynamics to account for high temperature and real gas effects, and allows for any fuel (for which the detailed chemical information is known) to be used. It can create an engine deck for a given design point (Mach, altitude, and angle of attack) that covers a predetermined range of off design points [4]. Using the external inlet geometry as inputs, RAMSCRAM is able to calculate the pressure distribution across the inlet. This essentially enables the user to have a separate drag polar for the inlet.

Geometry Modeling

Rapid Aircraft Modeler (RAM) [5] was used to specify the missile geometry because it gives a designer the ability to parametrically input geometrical parameters, and output the complete geometry in a format compatible with many of the commercially available aerodynamic analysis codes.

Aerodynamics

The aerodynamics analysis utilized commercially available codes that conduct aerodynamics based on user specified geometry. The Boeing developed *BDAP* [6] code was used for viscous drag analyses. *AWAVE* [7], developed by NASA, was used for inviscid supersonic wave drag. Finally, the McDonnell-Douglas developed *SHABP* [8] code was used for inviscid hypersonic pressure drag and stability derivatives.

Structural Analysis

The structural analysis was conducted using a MATLAB written routine that calculates the missile structure weight based on the fuel weight necessary to complete a predetermined mission, as well as any critical conditions at which the missile undergoes heavy loads. This is done so that the missile does not exceed the maximum allowable stress for the selected material. In addition, the routine conducts a complete weight and balance assessment so that the center of gravity (C.G.) location is coupled with the center of aerodynamic pressure of the tail fins, as discussed in the Stability Analysis section.

Stability Analysis

The stability analysis routine was an internally developed MATLAB code that was used to size the tail of the missile based on the C.G. location at the critical point of the mission. The routine was written to minimize total drag of the fins, while providing the necessary surface area needed to create the lifting force for maneuverability. The fin size was constrained to meet a maximum missile span constraint.

Trajectory and Sizing

The trajectory analysis used in this study included MATLAB code that sized the missile for maximum range. The trajectory profile was coupled with the sizing because the specific trajectory was not known.

Because the booster was separate, it was sized to carry the cruise portion of the missile from launch to a selected altitude and Mach number. The booster trajectory was determined through a time step integration approach, which uses the forces on the vehicle to differentiate the position and velocity state vector of the vehicle at a point in time. This results the acceleration, thereby yielding the new position and velocity for the next time step.

Once the booster separated, the ramjet cruise section trajectory was determined with the following segments: 1) after booster drop off, climb to cruise altitude (where lift = weight) and accelerate to cruise Mach, 2) cruise climb at constant Mach, at best altitude (cruise climb) until fuel runs out, and 3) adjust angle of attack to achieve best lift to drag ratio (L/D) for maximum range glide and impact.

Integration of Disciplines for Sizing and Synthesis

The methods discussed for the analysis of the different disciplines show how each discipline is dependent on at least one of the others for a complete and accurate analysis; consequently, the analyses needed to be integrated. To do this, an environment that could integrate the UNIX based disciplinary codes with the Microsoft Windows based inlet, trajectory, sizing, structural, and stability analyses MATLAB codes was needed. Along with linking all the analysis tools together, the sizing and synthesis environment must be robust to allow for a design space exploration leading to an optimized point design.

Integration of the different codes was achieved using iSIGHT and additional MATLAB codes. iSIGHT [9], a program that integrated simulation codes, was used to execute the codes correctly, keeping track of the design variables and responses. The code also recorded variables that were passed between the individual codes, allowing them to communicate. Additional MATLAB scripts were needed to compile the separate drag polars and engine deck into a usable format for the trajectory and sizing analyses. The PC based program GroundControl [10] was used to interface the MATLAB codes with the UNIX side. The complete integrated sizing and synthesis environment is shown in Figure 2.

The integration begins with the inputting of design variables, which for this study include the design mission and initial geometry assumptions. Cross sectional geometry of the missile was predetermined in a fuselage cross sectional geometry optimization based on aerodynamic analysis described by Won, Pfaender, and Levine [11]. Only the length of the breathing cruise section and the booster varied. They were both given an initial guess value. Design mission parameters included the Mach and range for the cruise section, and the Mach and altitude at which the booster burns out and separates, and the ramjet cruise section begins its climb. These inputs were set in the iSIGHT environment, and passed to the MATLAB based inlet analysis code. Design cruise Mach number and nose height were taken by the inlet code and used to design the inlet. The inlet analysis then passed the inlet geometry and flow conditions back to the UNIX side for the propulsion and aerodynamic analyses. First, the inlet geometry was given to the RAM so that the entire missile geometry could be created, and then converted to a usable format for the aerodynamic analyses.

The aerodynamic characteristics of the geometry were determined by combining the results of different aerodynamic analysis tools, AWAVE, BDAP, and SHABP. Separate drag polars were created for the ramjet/booster configuration and also for the ramjet cruise section. RAMSCRAM created the engine deck using the inlet geometry and flow conditions and the booster/ramjet takeover condition at its design point. As explained earlier, the aerodynamic analysis of the inlet was done in RAMSCRAM, so it too created an inlet drag polar. At this point, the UNIX based disciplinary analyses were completed, and the four drag polars, the engine deck, and the stability and control derivatives were sent back to the Windows based MATLAB environment to complete the sizing routine.

The sizing routine began with the compilation of the four drag polars and incorporating them into one usable format for the trajectory codes to use. This is where the inlet drag polar was added to the fuselage drag polars. In addition, the engine deck was setup in a format compatible with the trajectory analysis.

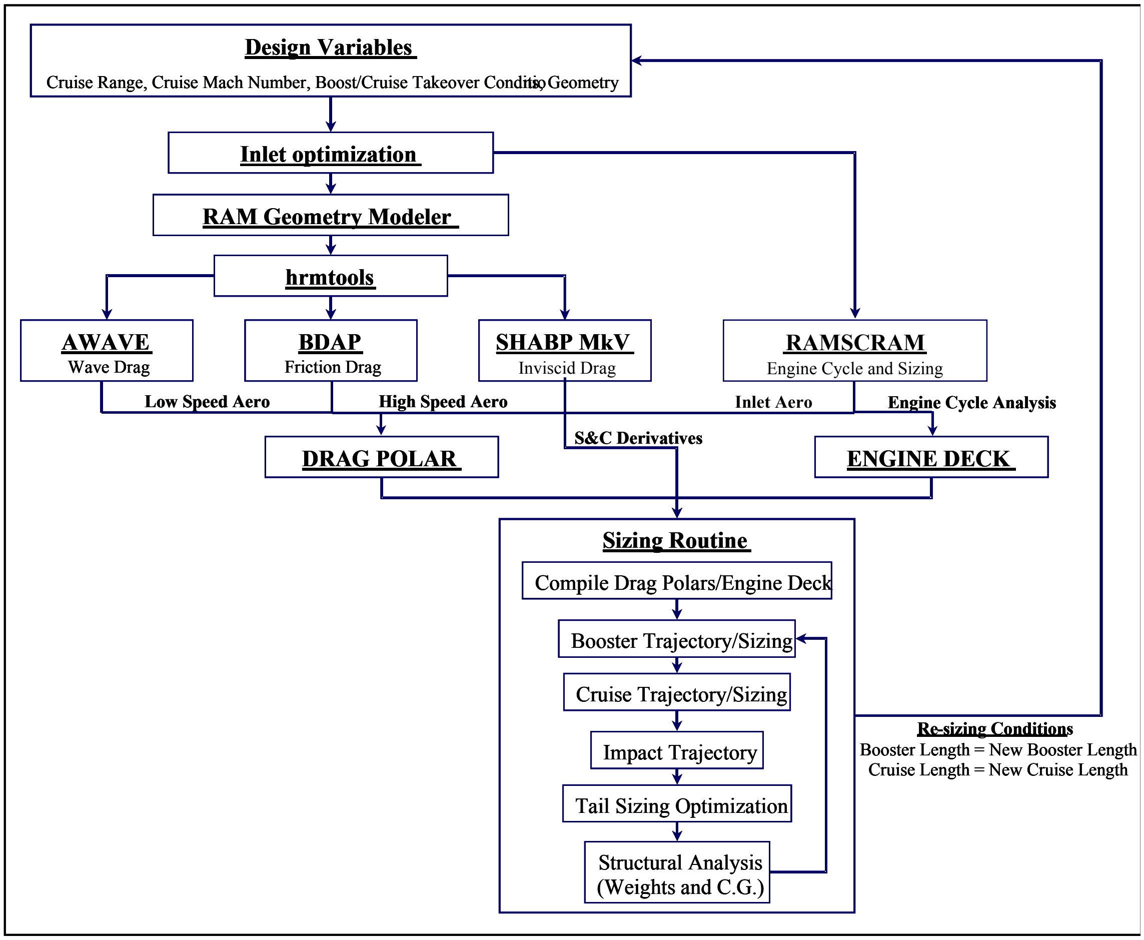

Figure 2: The Integrated Sizing & Synthesis Environment

Once the required cruise fuel weight was known, a structural analysis determined the structural weight of the missile. This was coupled with a tail fin sizing and optimization routine. The coupling of the structural and stability and analysis allowed for weight balance considerations to be taken into account to size the tail. This allowed for a complete determination of the cruise section empty weight. In addition, the structural analysis calculated the required cruise section length based on the required volume.

Once the empty and fuel weights were known, the total weight of the vehicle was known at the ramjet takeover point, which is essentially the payload that the booster has to carry. The total booster weight was added to the total cruise weight, and the new guess launch weight was used to resize the booster. This process was iterated until the launch weight input to the booster sizing analysis equaled to the sum of the all the weights calculated in the booster and cruise sections. This is the point at which the internal iteration ends, and the overall iteration on geometry begins. The total booster length calculated from the booster sizing analysis, and the cruise section length calculated from the structural analysis was compared to the initial lengths input to the environment. The entire process was then iterated until the lengths calculated were within a certain tolerance of the lengths input to the environment.

Design Space Exploration & Determination of Feasibility

The main objective of the design space exploration is the determination of feasibility. A Design of Experiments was run for the variables given in Table II. To determine which variables were to be explored with the DoE, a screening analysis was required of the design variables to determine which variables cause greatest variability of the responses. The designers of this environment determined from experience with the sizing environment that the cruise conditions (Mach and range) and the booster/ramjet takeover conditions (Mach and altitude) had the greatest impact.

Table II: Variable Ranges for the Design Point DoE

Design Variable	Lower Bound	Upper Bound
Cruise Mach	4	5.25
Cruise Range (km)	800	1400
Takeover Mach	3.5	4.75
Takeover Altitude (ft)	50,000	70,000

Note that for the DoE, ranges were assigned to the variables. The lower bound of the cruise Mach came directly from the RFP's requirement that the maximum Mach number may not be below Mach 4. The upper bound was reduced from the RFP specified Mach 6 to Mach 5.25 because the code became unstable when the cruise Mach went much above Mach 5.

Once the metrics of interest were determined, the creation of the metamodel commenced. These responses were launch weight, total length, booster impact range, total range, time to target, and average ground speed. Recall that average ground speed was added as a method for relating total time to target to range. The original requirements given in the RFP gave minimum and maximum goal for time to target and range, the requirements did not specifically match a certain range with a time to target. Trying to achieve the highest possible range with the lowest possible time to target was a bit nebulous, but trying to achieve the highest possible average ground speed was a more concrete goal.

Using the JMP statistical software, Response Surface Equations were created from the results of the DoE. Figure 3, shows the partial derivative of each response (ordinate) to each design variable (abscissa) in a parametric requirement space exploration. Together, they allow the designer to quickly determine the impact of changing design parameters on the system level metrics.

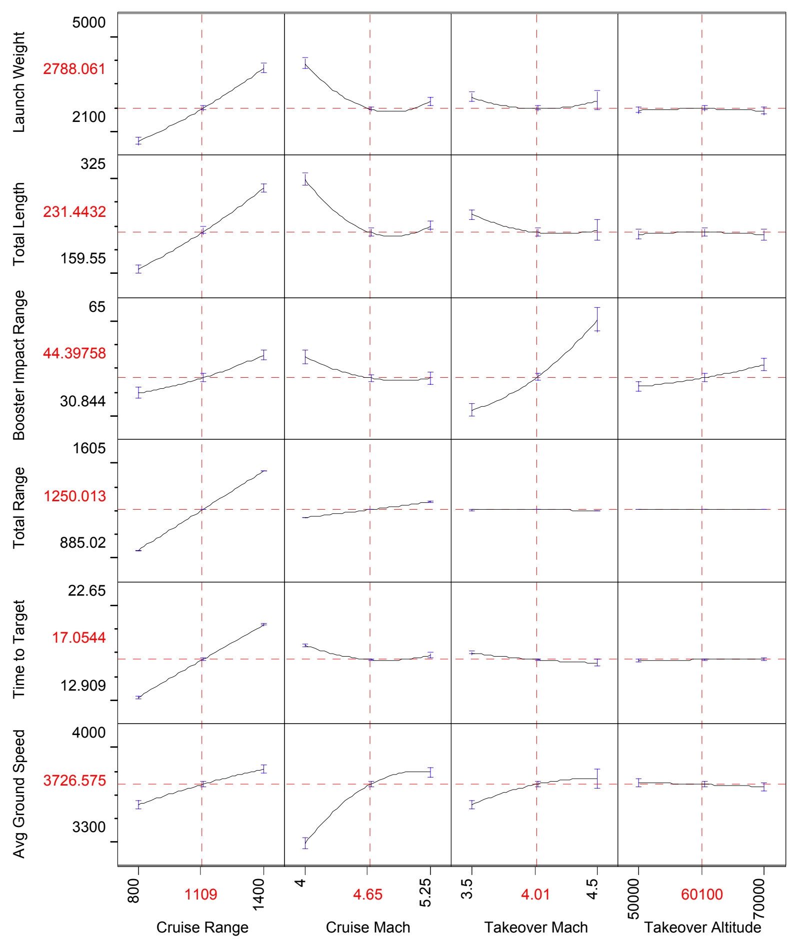

Figure 3: Parametric Requirement Space Exploration Environment

Visualization of Design Space

Once the metamodel was created, the design space could be better visualized using tools in JMP. The contour profiler plots contours of the responses versus any two design variables, in the form of a dynamic tradeoff environment. Constraints can be overlaid on these contours, to show the feasible design space. Because the design space is represented as a metamodel, contours can be quickly updated to reflect the effects of changing requirements.

The design space around the booster/ramjet takeover condition is shown in the left column of Figure 4. The graph on the top left shows how takeover altitude and takeover Mach are greatly constrained by total length and booster impact range. This shows that in order to not exceed the 50 km booster impact requirement, and not design a missile that was greater than 256 in, the takeover Mach had to be around 4, and the takeover altitude had to be below 57,000 ft. The shaded area is the unfeasible space that would violate the constraint, and the open white space on the right side of the graph is the feasible space.

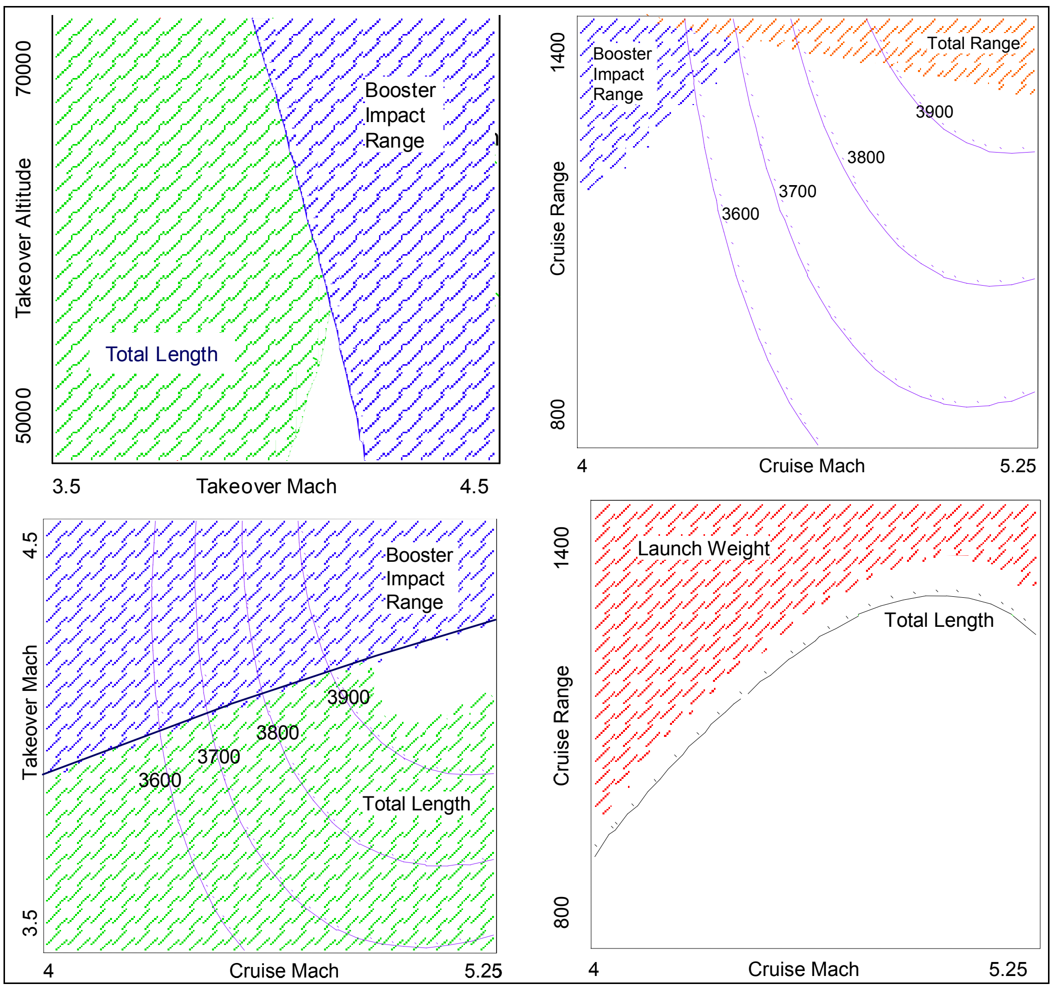

Figure 4: Booster/Ramjet Takeover (Left) and Cruise Segment (Right) Feasible Design Space Explorations Shown in a Dynamic Tradeoff Environment

The bottom left graph shows how the takeover and cruise Mach numbers were constrained by the total length and booster impact range. In addition, several contours of increasing average ground speed are overlaid (shown increasing from 3600 fps to 3900 fps). This shows that increasing the average ground speed to 3900 fps did not diminish the feasible design space of the takeover condition, and may have been beneficial to overall performance.

The graphs on the right column of Figure 4 show how the requirements affected sizing for the cruise condition. The top right plot shows how cruise range and cruise Mach were constrained by the 50 km booster impact range requirement, and a 1500 km maximum range constraint. The designers believed that designing the missile to fly farther than the RFP maximum range given by the RFP would be an "over-design".. In addition, recall that the input "cruise range" is how far the missile travels until it runs out of fuel, and the output "total range" includes the un-powered glide. Here, the increasing contours of average ground speed greatly closed in the feasible design space. An average ground speed of 3900 fps did not affect the feasible space of the booster/ramjet takeover condition, but limits the cruise Mach such that it may not be less than about Mach 4.8, and the cruise range may not be less than about 1200 km. The bottom right plot shows how the physical requirements constrain the cruise condition. The contour for total length is not shaded in because the constraint of the 3400 lb launch weight requirement would not be visualized. This plot shows that the physical requirements did not limit the cruise Mach in any way, but did limit the cruise range.

Design Point Optimization

Once the design space was understood, the design point could be optimized using the metamodel. JMP has a desirability function that essentially allows the user to maximize an Overall Evaluation Criteria (OEC) function. The user defines relative weighting for the responses, and sets targets values for each of those responses. Additionally, JMP allows each response to be constrained, so as to ensure the optimal solution is feasible. These desirability functions were used to find the optimized setting for each design variable. Again, the optimization used the metamodel to map the design variables to the system metrics so that the optimal point could be found almost instantaneously.

Each variable was then set to maximize the "desirability". The desirability is the sum of how close each response is it is to its optimum setting. For example, launch weight was set to have a maximum desirability when it was as light as feasibly possible, with an upper limit of 3400 lb. This response was traded off with the desirability of the other responses by using relative weightings. The average ground speed was maximized with a lower limit such that the missile could at least reach a target of 1000 km within 15 minutes. The effect of each design variable on the desirability of the entire system is shown in Figure 5. The maximum possible desirability was achieved with the optimal settings of each design variable.

To the size a missile that meets the optimized design mission parameters, the values for the design mission from the desirability curves in Figure 5 were used as the final inputs to the integrated environment in Figure 2. Recall that metamodels are only used when a design space is to be explored. When a point design is desired, and total run time is reasonable, it is not necessary to contend with the inherent error of a meta-model. In addition, the meta-model only kept track of the four outputs used in the mission optimization, where as the integrated environment kept track of every detail of the missile, such as fuselage skin thickness, inlet ramp angles, engine performance parameters, and trajectory profile.

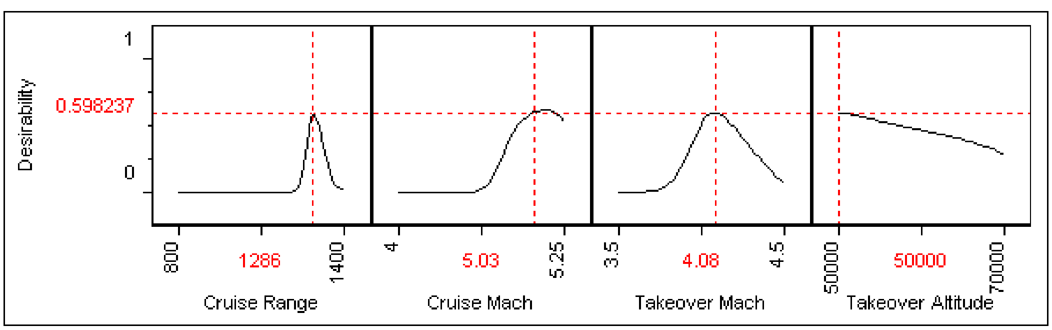

Figure 5: Desirability Curves for the Design Variables

The layout presented in Figure 6 shows an example of a cruise missile designed using the optimized design mission parameters. Note the level of detail achievable in the inboard profile, and the optimized fuselage cross section in the three-dimensional view.

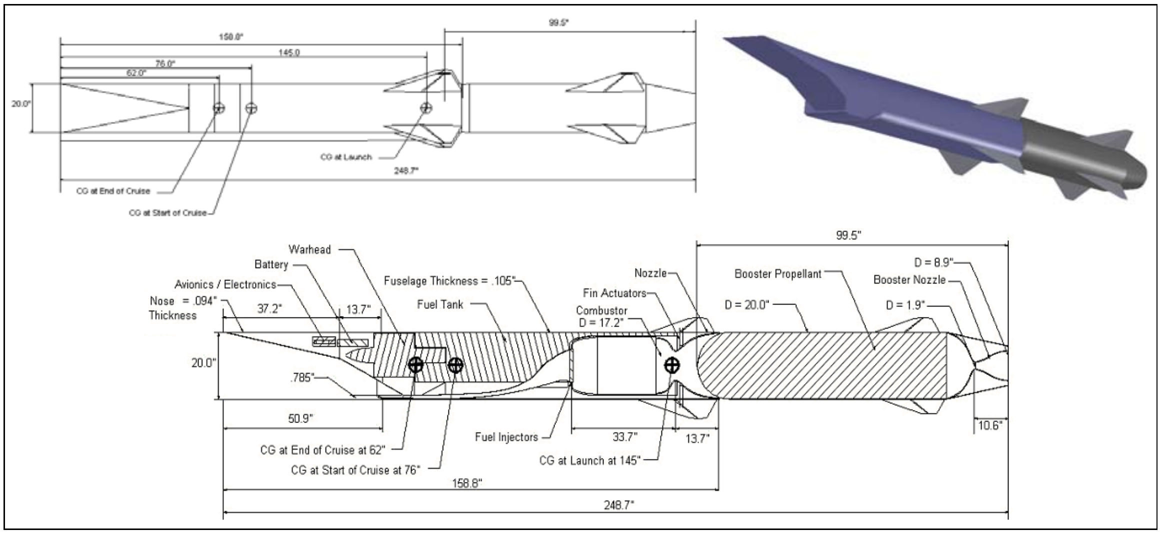

Figure 6: Hypersonic Cruise Missile Layout

The trajectory presented in Figure 7 shows the detailed time-stepped trajectory profile for the missile example given in this study. Note the time and altitude and/or time called out for the main mission segments. This illustrates the level of detail of the time-stepping trajectory.

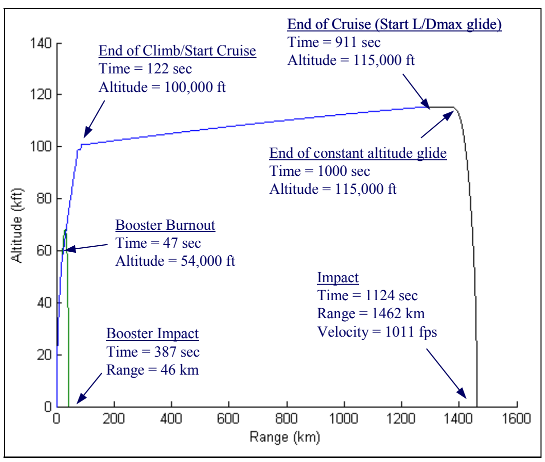

Figure 7: Maximum Range Mission Trajectory Profile

Quantification of Uncertainty

Once the design point was selected, the uncertainty associated with that design point was quantified. The designers were again limited by time constraints, so the uncertainty analysis was limited to analyzing the effects of uncertainty in UNIX based disciplinary analyses on the sizing and performance of the missile. This was necessary because the team lacked the ability to accurately measure the fidelity of individual codes. A new metamodel was created that related error in disciplinary analyses to the sizing and synthesis code. A new DoE was run on ranges of error factors as they were applied in the sizing and synthesis analysis. New RSE's were regressed against the inputs so that a Monte Carlo analysis could be performed to determine the confidence levels of meeting constraints.

The effects of error in the aerodynamics and propulsion codes were studied by applying error factors to the outputs of the aerodynamics and propulsion codes. A new DoE was then run for the given design point, over a range of uncertainty factors to create a metamodel relating the error factors to the responses tracked in earlier phases. For each parameter, a nominal range of ±5% was studied, giving the ranges shown in Table III. This range was chosen to maintain the stability of the entire integration process.

Table III: Uncertainty Factors with Associated Ranges

Parameter	Lower Bound	Upper Bound
I_{SP}	0.95	1.05
Thrust	0.95	1.05
Lift	0.95	1.05
Drag	0.95	1.05

The error factors were directly applied to the values used in the integrated sizing and synthesis environment. Figure 8 shows a close up section of the environment presented in Figure 2, showing where the uncertainty error factors were applied. Note that the sizing routine (trajectory, sizing, structures, stability) uses the drag polars and engine deck with the uncertainty factors already applied.

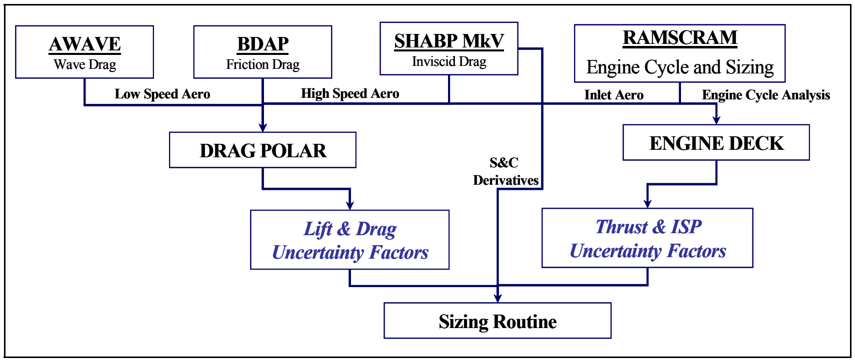

Figure 8: Uncertainty Error Factors Applied to the Integrated Sizing and Synthesis Environment

A Monte Carlo analysis was performed by analyzing thousands of possible combinations of the error factors. At roughly fifteen minutes a run, ten thousand iterations through the sizing and synthesis environment would take about 104 days to complete. Performing a Monte Carlo analysis on the metamodel, however, allowed 10,000 trials to be run in about a minute.

Figure 9 shows the dynamic uncertainty environment that was created for the uncertainty analysis. Note the trends associated with a specific error on a specific response. It is important to remember that each point was designed for the same cruise range, therefore the total range does not vary greatly.

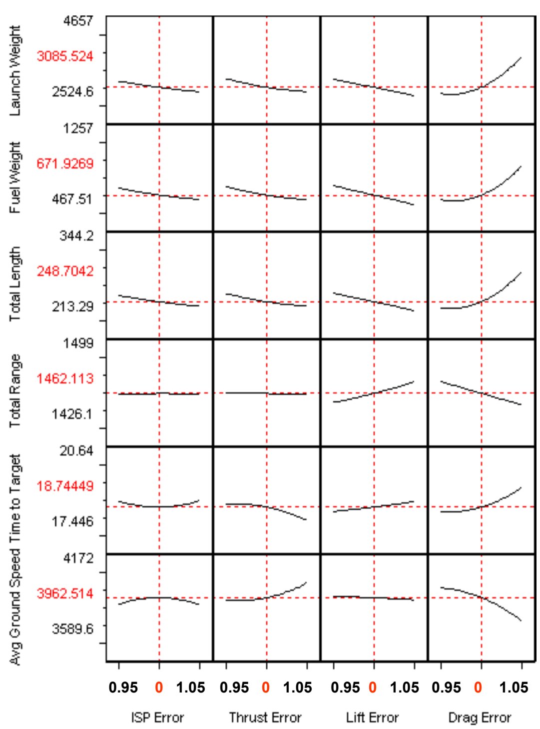

Figure 9: Dynamic Uncertainty Analysis Environment

Only the error associated with the aerodynamic terms on the un-powered glide segment varied the total range. Even with a lower I_{SP}, if the design cruise range does not vary, only the fuel and total weights increase. As discussed with earlier prediction profiles, this new metamodel made it possible to determine the effects of any combination of error factors on the design of the missile.

The Monte Carlo analysis was conducted by studying the effects of 10,000 random combinations within the range of each error variable. A triangular distribution was placed on the error factors, meaning that the likely value picked would be close to zero, or the no error term. The values at the tips of the triangle would be less likely to be chosen.

After running 10,000 cases, the values for launch weight and total length were analyzed using a Cumulative Distribution Function (CDF) shown in Figure 10. A CDF is a plot uses the frequency of a certain response to calculate the associated probability of that response being below (or above) a target metric. Recall that the purpose of this uncertainty analysis was to determine the confidence that a feasible missile could be designed within the VLS constraints, given the error of the aerodynamics and propulsion codes. From the CDF, there was an 88% confidence associated with designing under the 3400 lb weight limit while maintaining the same performance. Additionally, there was a 63% confidence associated with designing a missile under the 256-in length limit while maintaining the same performance.

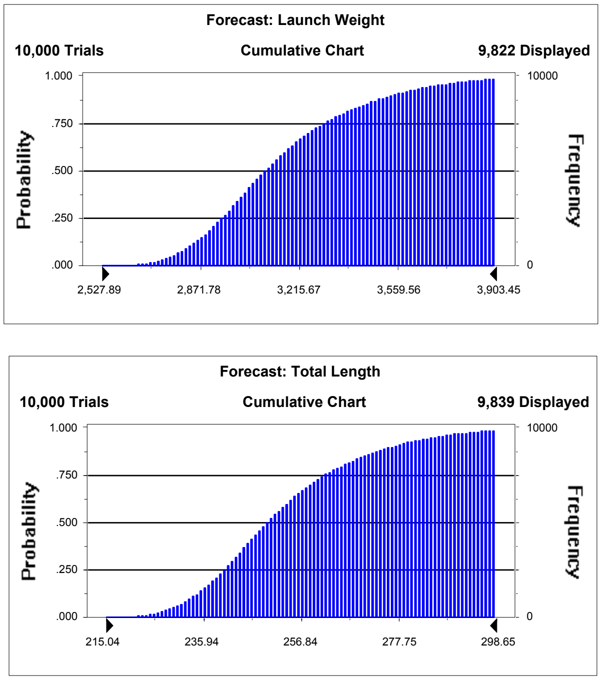

Figure 10: Cumulative Distribution Functions for Launch Weight (Top) and Total Length (Bottom)

At this point, the designers reviewed the entire sizing process. If the confidence levels were unacceptable, a different design point would have been chosen. In fact, the entire process can be repeated in a matter of hours. The desirability's associated with certain responses (recall Figure 5) could be altered by manipulating the OEC, and the uncertainty analysis rerun. The quantification of uncertainty required additional manipulation of the integrated sizing and synthesis environment.

Conclusion

This paper presented the method used to create an integrated sizing and synthesis environment for the design of air-breathing hypersonic cruise missiles. The creation of the integrated sizing and synthesis environment allowed for a thorough design space exploration. Through a design space exploration, the values of design variables that led to optimal (or near optimal) responses could be determined. This led to an optimal point design that best meets the ranging and sometimes conflicting requirements.

This environment may serve as an enabling tool with many applications. Entities that develop requirements could have the ability to see the impacts of changing those requirements on the design of the missile. The design community could parametrically map the missile design to its ability to meet the requirements. This gives the ability to examine the design space with more depth than previously available, and reduces the risk through the quantification of uncertainty. The technology community could see the impacts of technology infusion on system level metrics.

If the error associated with any of the disciplinary analyses is unacceptable, the modularity of the integrated sizing and synthesis environment allows for quick replacement of analysis approaches. A new DoE could be run to determine a new design space exploration, and the entire process repeated. This is a very useful approach, and beneficial in that this process allows for the customer to be more involved earlier on in the design process.

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