A PROBABILISTIC APPROACH TO THE CONCEPTUAL DESIGN OF A SHIP-LAUNCHED HIGH SPEED STANDOFF MISSILE

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Abstract

This paper focuses on the application of advanced design methodologies developed by Georgia Tech's Aerospace Systems Design Laboratory (ASDL) to the conceptual design of a hypersonic air-breathing ship-to-surface cruise missile. This approach uses an integrated, parametric environment, that brings more physics based knowledge into early phases of design, thus allowing the designer to have a thorough understanding of the entire design space. Response Surface Methodology (RSM) and probabilistic methods allow the designer to then generate a field of designs, instead of just one point design. A High Speed Standoff Missile (HSSM) was required to deliver a 250-lb warhead to time critical targets with a stationary dwell time between five and fifteen minutes, at a range of up to 1,500 km. The primary drivers for a successful design were shown to be minimum time to target, affordability, and compatibility with the Vertical Launch System (VLS) currently used on many of the United States Navy's cruisers and destroyers. Included is an explanation of the physics based tools used to perform the various disciplinary analyses, and their use to construct metamodels allowing for design space exploration and robust design simulation, as well as a quantification of the uncertainty in the design parameters.

Motivation

The primary motivation behind this study was the need for a ship-launched missile with the capability to strike time critical targets (TCT's) in a timely fashion, with the secondary capability to strike certain hardened targets. A Request for Proposal (RFP) was written to outline this need for a Ship Launched High Speed Standoff Missile (HSSM). The Tomahawk cruise missile is the Navy's current primary solution for attacking long-range surface threats. However, because it is a subsonic weapon, it is ill suited for use against suddenly appearing or hiding targets at a distance, such as Scud theater ballistic missile (TBM) launchers.

During Operation Desert Storm, Coalition forces encountered difficulty in destroying Iraqi Scud launchers that were being used to bombard friendly forces and attempt to draw Israel into the conflict. A Scud launcher could be readied to fire within 30 minutes or less by their crews, who had gained great proficiency from the Iran-Iraq war several years earlier[*1*]. However, once the Scud was launched, the launcher could be hidden completely within 5 minutes [*2*]. This left little time for a response, and the Coalition was forced to rely on orbiting strike aircraft to be called in when a launch was detected. For initial inventory ratios of 10 TBM's per Transporter Erector Launcher (TEL), reductions of about 80% are possible with probabilities of successful post launch TEL kill of about 0.5, (this includes reductions of 50% for only a probability of 0.2). This is under the assumption that TEL's are more expensive than missiles [*3*]. Thus, a great reduction in enemy launch capability would be gained even if the TEL's were destroyed after launch. The RFP accounted for this by requiring that the missile must be capable of such striking targets 500 to 1500 km in range within 5 to 15 minutes. The HSSM was also required to cruise between Mach 4 and 6, and impact targets at a velocity between 2,000 and 4,000 ft/s.

A hypersonic missile, combined with an advanced command, control, communication, computers, intelligence, surveillance, reconnaissance (C4ISR) network would enable precise and timely strike capability against such targets, possibly allowing a strike to occur before the enemy can employ the launcher. A hypersonic system has the added benefit of high kinetic energy on impact, reducing the need for a large warhead, and affording some degree of penetration against fixed or hardened targets such as command bunkers. Additionally, a hypersonic missile has the benefit of survivability due to high altitude cruise flight and high speed terminal flight. The RFP also stated that the HSSM will need to cost less than

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$600,000 per unit, making it an affordable solution as well. This would allow the HSSM to be used for more traditional standoff missions other than solely against TCT's.

Finally, the RFP demanded that the HSSM was compatible with the Mark 41 Vertical Launch System (VLS). The Mk 41 VLS is produced by United Defense, and is deployed on AEGIS-equipped Ticonderoga-class cruisers and Spruance- and Arleigh Burke-class destroyers. It is also to be deployed on several next-generation warships, and incorporates several advanced features such as automated fire suppression systems, climate control, and redundant fire-control systems [*4*]. For a missile to be VLS compatible, it must weigh less than 3200 lb, have a cross section that fits into a 21 x 21 in^2 area, and not be longer than 256 in.

Approach

The design method used in this study was adapted from ASDL's generic *TIES* methodology (see methods referenced in [*5*]). The generic methodology is essentially a systematic approach to design, that strives to bring more knowledge to earlier phases of design, thus allowing the designer to design for multiple objectives, as well as for affordability, earlier. When adapted to missile design, the method can be broken into five steps:

1. Define the Problem
2. Define the Concept Space
3. Identify Modeling and Simulation Environment
4. Investigate the Design Space
5. Determine System Feasibility and Identify the Best Design

Problem Definition

Defining the problem is the first step required to be taken when solving any problem. The purpose of this step is to ensure that the objectives, or customer requirements, for the design are fully understood by the designer. Problems often have many objectives, and an understanding of the relative importance of each objective is an essential element of a good design. In this step, each of these requirements is weighed, so the designer has a quantitative assessment of the priority of each of the different requirements or objectives. The problem definition should be conducted interactively with the customer so as to ensure that his or her voice is heard. This assessment of priority is in the form of a relative weighting for each requirement. Also, in this phase of design, the relationship of the customer requirements to the engineering characteristics, and the tradeoffs between the various characteristics are examined. Many tools exist which aid in this process, such as the Integrated Product Process Development methodology [6]. For the purpose of this study, the customer requirements were taken from the RFP. Additionally, a panel of industry specialists served as both customers and advisors.

Concept Space Definition

In the second step of the design methodology, the design space is defined. Design space can be explained as the complete list of alternatives that are being considered as solutions for the design. Characteristics of each alternative can be either continuous, such as a missile fuselage's length, or discrete, such as the type of propulsion system. A morphological matrix, given in Figure 1, was used to list every possible system characteristic that was considered to be a reasonable candidate for the hypersonic missile. Note that different types of system and sub-system possibilities listed, and that the main sources of hypersonic air-breathing propulsion are highlighted. Figure 1 illustrates the vast number of alternatives that were considered. Depending on the detail of the morphological matrix, there are an endless number of system characteristics, making the number of alternatives essentially infinite. The RFP, however, explicitly stated a desire for an air-breathing, hypersonic missile, and consequently, all such missiles initially made up the design space.

The designers were limited in both their ability to model each alternative, and in resources, making it infeasible to analyze the complete design space. Within this phase of design, consequently, the "best" propulsion system was selected, which limited the design space considerably.

Modeling and Simulation

Once the design space to be examined is determined, the modeling and simulation environment that the designer would use to analyze the design space needs to be formulated. There are certain characteristics that this environment must have. First, its analysis must be based on physical relationships. Design within aerospace vehicles too often relies on historical relationships, making it impossible to truly innovate within design. Second, the environment must be integrated and automated. Each discipline within aerospace relies heavily upon the others, meaning that true designs must analyze each discipline simultaneously. Parameters must pass from one disciplinary analysis to another to ensure that system level parameters can be assessed. Finally, the environment must be parametric. A parametric environment allows any design that fits into the design space to be analyzed.

In many instances, this environment exists, or can be easily developed by modifying tools that already exist. Unfortunately, the designers had no such tool available to them. Consequently, much time was spent developing such an environment. This exhaustive process consisted of finding and learning to use disciplinary analysis tools that existed, creating tools when none existed or where available, and linking all of them together.

		1	2	3	4	5	6	7	8
Propulsion	***Booster Type***	**Integrated**	**Separate**	**Both**					
	Booster Fuel	**Solid**	**Hybrid**	**Gel**					
	Booster Grain	**Constant Thrust**	**Boost-Sustain-Boost Thrust**	**Progressive Thrust**	**Boost-Sustain Thrust**	**Regressive Thrust**			
	Cruise Propulsion	**Solid Fuel Ducted Rocket**	**Liquid Fuel Ramjet**	**Solid Fuel Ramjet**	**Liquid Fuel Scramjet**				
Structures	***Body Type***	**Cylindrical**	**Elliptical**	**Complex Lifting Body**	**Waverider**				
	Construction	**Monocoque**	**Integrally Hoop Stiffened**	**Integrally Longitudinal Stiffened**	**Hoop/Longitinal Stiffened**				
	Cooling	**Active Cooling**	**External Insulation**	**Internal Insulation**	**Internal & External Insulation**	**Warhead Heatsink**	**Ablative Cooling**	**None**	**Fuel Cooling**
	Structure Type	**Hot Stucture**	**Cold Structure**						
	Materials	**Titanium Alloy**	**Ceramic Matrix Composite**	**Metal Matrix Composite**	**Carbon Matrix Composite**	**Aluminum**	**Superalloy**	**Combination**	
Electronics	***Power Supply***	**Li Battery**	**Thermal Battery**	**Alternator**	**Thermal Electric Generator**	**Fuel Cell**			
	Communications	**Continuous Update**	**Midcourse Update**	**None**	**BDI**				
	Electronics Cooling	**None**	**Prestored Coolant**	**Insulation**	**Fuel Cooling**	**Ablative Cooling**			
Stability & Controls	***Control Surfaces***	**Tail**	**Canard**	**Wing**	**Thrust Vectoring**	**Combination**			
	Control Power	**Electric**	**Cold Gas**	**Hot Gas**					
	Fixed Surfaces	**Tail**	**Canard**	**Wing**	**Combination**	**None**			
	Surface Stowing	**None**	**Folded**	**Wraparound**	**Switchblade**				
	Maneuvering	**Skid-to-turn**	**Bank-to-turn**	**Rolling Airframe**					
	Stability	**Static Stability**	**Relax Static Stability**	**Unstable**					

Figure 1: Hypersonic Missile Morphological Matrix of Alternative

Design Space Exploration

Once the environment was created and integrated, the design space could be fully examined. A complete examination of the design space requires an understanding how each design parameter effects the design. If the simulation tool used to examine the design space is easy and does not require a significant amount of time to run, this understanding of the design space is simple to achieve. Any design can be generated easily with the modeling environment. If the simulation is exhaustive, however, it is not feasible to rerun the simulation for each alternative.

A metamodel, or an approximation of the simulation, can be created to replace the complex simulation environment. Response Surface Equations (RSE's) are curve fits (of any order) that approximate the code. The RSE's used in this study are second order curve fits, meaning that three data points are used to create the curve. The designers selected to create a RSE metamodel to use in place of the simulation. To create the RSE's, each case in a predefined, orthogonal Design of Experiment (DoE) was run through the simulation. A DoE was used to minimize the number of cases that were required to be run through the simulation to determine the relationship between the responses and the design variables. The responses generated from the simulation were then regressed against the input design variables to create the RSE's; one RSE was generated for each response that was tracked. The metamodel was then used to relate any set of design variables to the responses, essentially instantaneously.

Within this phase of design, statistical software packages, such as JMP [*7*], allow users to visualize design space and optimize for multiple objectives using the metamodel. The visualization of the design space comes from plotting the partial derivatives of each response to each metric. The software also uses the RSE's to select optimal design variable settings based on user input target responses with given relative weightings.

Examination of Feasibility

This step of the design phase goes hand in hand with the design space exploration. Once the design space is understood, the feasibility of any alternative within the design space can easily be assessed. Statistical packages allow the user to plot constraints that allow the designer to quickly determine feasible and infeasible design space. Another examination of feasibility involves the use of probabilistic methods. Because the responses can be quickly related to the design variables, thousands of alternatives can be generated and analyzed in real time. This can be done by using a Monte Carlo random number generator to generated thousands of cases, which are all run through the metamodel. A distribution is placed on the input variables to reflect the entire design space. Analyzing the distribution of the responses shows the designer what percentage of the design space yields feasible results.

In the same way, metamodels can be built to relate responses to noise (or uncertainty) variables, such as the error of a disciplinary code. A Monte Carlo analysis would then be used to generate the thousands of noise variables (with a distribution selected to model the expected distribution). The distribution of the responses would quantify the uncertainty of the responses.

Propulsion Baseline Down Selection

As was earlier alluded to, the first two steps of the design process were used to select the propulsion system to propel the high speed standoff missile. First, the problem was defined by clarifying the requirements that were stated by the RFP. The noteworthy customer requirements that were deemed most important were range, time to target, accuracy, and acquisition price because they directly correlated to the total system effectiveness of the missile. These requirements were all given a maximum relative weighting. Impact speed, reliability, and storage life were given less of a priority.

Once the customer requirements were understood and quantified, the design space could be limited. Before the down selection, the design space consisted of essentially every air-breathing hypersonic missile combination possible from the matrix of alternatives given in Figure 1. Due to time constrictions, the designers elected to only select the propulsion system for the missile at this time. The intent then became not to design missiles that would be refined in later stages, but to design a missile with each type of the following propulsion systems that could be used to compare the propulsion systems, thus selecting the propulsion system that best meets the customer requirements.

1) Ducted Rocket
2) Liquid Fuel Ramjet
3) Solid Fuel Ramjet
4) Liquid Fuel Scramjet

To do this, an existing missile with each of the propulsion system alternatives was used as a baseline and designed to best meet the RFP requirements. The missile was designed as accurately as possible, but because of the time constraints, many of the methods used to design the missile were "back of the envelope" calculations, such as those outlined by Fleeman [*8*]. The use of these calculations required many assumptions, but the assumptions were held constant for each missile to ensure a fair comparison. Also, the technology advancement assumed for each missile, such as the advancement of the fuel type was held constant. The basic characteristics of each of the missile that resulted from this preliminary sizing analysis are summarized in Table I. These characteristics were used to evaluate the ability of each propulsion system to meet the customer requirements.

Table I: Summary of Missile Characteristics Used for Down Selection

	Ducted Rocket	Liquid Fuel Ramjet	Solid Fuel Ramjet	Scramjet
Maximum Range (km)	955	1500	1500	1172
Total Time to Target (min)	6.12	5.53	5.82	3.82
EMD Cost ($100 M)	4.07	4.89	4.49	5.60
Propulsion Risk	11.80%	11.53%	12.00%	10.93%
System Risk	3	4	6	9

After each of the four missiles were designed, a Multi Attribute Decision Making (MADM) process was used to rank the alternatives from best to worse. The MADM technique used was Technique for Ordered Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS creates a positive and negative ideal solution, consisting of the best and worst characteristics, respectively, of the solution set. There were six criteria that the missiles were compared on: available volume, maximum range, total time to strike a target 500 km away, cost, propulsion risk, and system risk. Propulsive risk reflected how much above the current state of the art the combustion temperature would have to be, and is given in a percentage above 4000 ^{o}F. System risk was simply a subjective measure of how risky the propulsion concepts were. It was quantified on a scale of 1 to 9.

TOPSIS accounts for various degrees of importance for each customer requirement by multiplying each metric by a relative weightings. Consequently, TOPSIS is heavily reliant on these weighting scenarios. Six weighting scenarios were considered, ranging being performance driven to being economic driven. In each scenario, except for the pure performance and the pure cost scenarios, the liquid fuel ramjet was the closest solution to the positive ideal. For this reason, the liquid fuel ramjet alone was brought to the next phase of design.

Modeling and Simulation Environment

In identifying the modeling and simulation environment, the best approach to analyzing every discipline involved in missile sizing is determined. Because no integrated environment existed, the designers were given the freedom to select the best code or method available to analyze each discipline. Therefore, an analysis tool was either selected or created.

Disciplinary Analyses

The disciplinary analyses along with their respective platform are listed in Table II. 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.

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

Table II: 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)

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 2 is calculated.

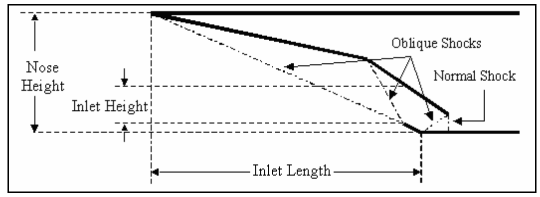

Figure 2: Inlet Analysis Configuration

Propulsion

The propulsion analysis consists of the *RAMSCRAM* FORTRAN analysis code developed by NASA [*9*]. It was designed for the cycle analysis of hypersonic, air-breathing propulsion systems, including ducted rockets, ramjets, and scramjets. It calculates 1-D flow properties at each component interface by marching through the engine flow path. RAMSCRAM 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 [9]. Using 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, as well as create an engine deck.

Geometry Modeling

Rapid Aircraft Modeler (RAM) [*10*] 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* [*11*] code was used for viscous drag analyses. *AWAVE* [*12*], developed by NASA, was used for inviscid supersonic wave drag. Finally, the McDonnell-Douglas developed *SHABP* [*13*] 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 required stability and 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. The booster 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. Once the booster separated, the ramjet cruise section would climb and accelerate under its own power to cruise altitude, cruise-climb at constant Mach, and finally descent 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. For this analysis, an environment that could integrate the UNIX based disciplinary codes with the MATLAB based inlet, trajectory, sizing, structural, and stability analyses codes was needed. Additionally, this environment must be robust to allow for a comlete design space exploration leading to an optimized point design.

Integration of the different codes was achieved using iSIGHT [*14*], a program that integrated simulation codes, and additional MATLAB codes. iSIGHT, was used to execute the codes correctly, keep track of the design variables and responses, and record variables passed between the individual codes. 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 [*15*] was used to interface the MATLAB codes with the UNIX side. The complete integrated sizing and synthesis environment is shown in Figure 3.

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. Only the length of the cruise section and the booster varied. 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. 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. RAMSCRAM created the engine deck using the inlet geometry 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 MATLAB based environment to complete the sizing routine.

The sizing routine began with the compilation of the four drag polars 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 organized in a format compatible with the trajectory analysis.

A structural analysis determined the structural weight of the missile based on the fuel required. The coupling of the structural and stability and analysis allowed for weight balance considerations to be taken into account to size the tail. The structural analysis calculated the required cruise section length based on the required volume.

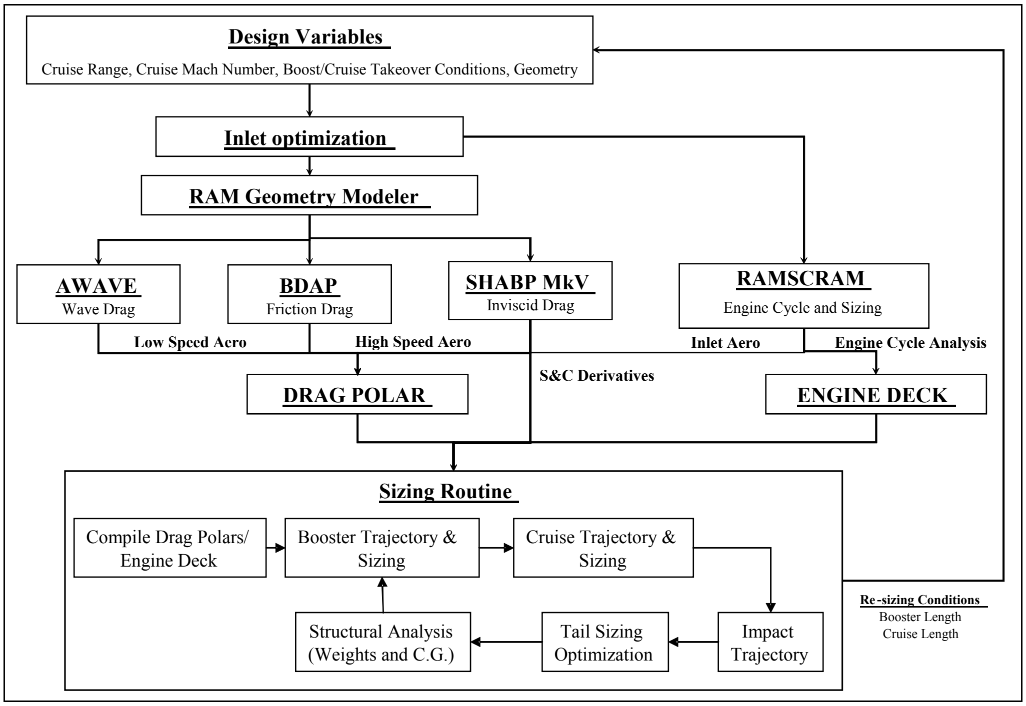

Figure 3: The Integrated Sizing & Synthesis Environment

The total weight at the beginning of the cruise portion 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. Now 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 and Evaluation of Feasibility

To examine the design space, distributions were placed on the inputs to the sizing environment. Using a Design of Experiments run for the variables given in Table III, a metamodel of the sizing environment was created. The designers of this environment determined that the cruise conditions (Mach and range) and the booster/ramjet takeover conditions (Mach and altitude) had the greatest impact on the variability of the design, and therefore used as the variables in the Response Surface Equations (RSE). Note that for the DoE, ranges were assigned to the variables. The lower bound of the cruise Mach came directly from the design requirements, and the upper bound was set to maintain the stability of the environment.

Table III: 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

The metrics of interest for the RSE's were launch weight, total length, booster impact range, total range, time to target, and average ground speed. Using the JMP statistical software, RSE's were created from the results of the DoE. The prediction profile, shown in Figure 4, shows the partial derivative of each response (ordinate) to each design variable (abscissa). The profiles allow the designer to quickly determine the impact of changing design parameters on the system level metrics.

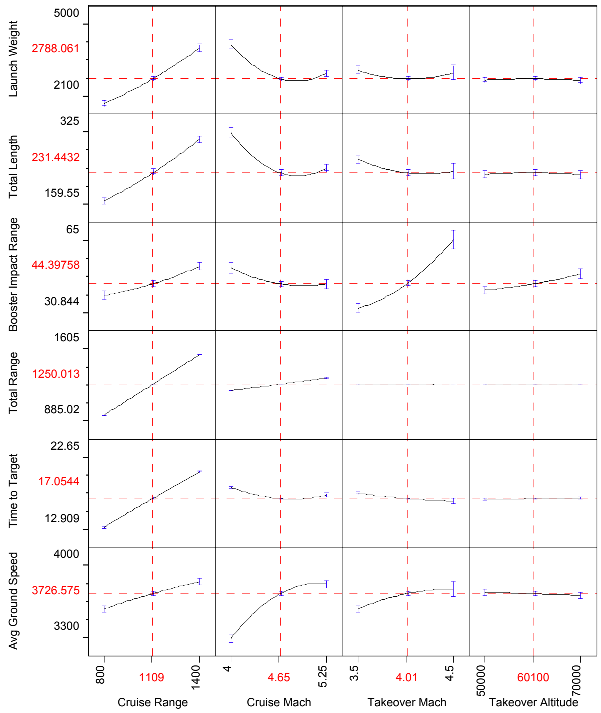

Figure 4: Parametric Dynamic Design Space Exploration Environment

Visualization of Design Space

Having the metamodel of the sizing environment, contour plots can be created to visualize the feasible design space. A contour profiler plots contours of the responses versus any two design variables, with constraints 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 Figure 5. This graph 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 6 shows how the requirements affected sizing for the cruise condition. Cruise range and 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.

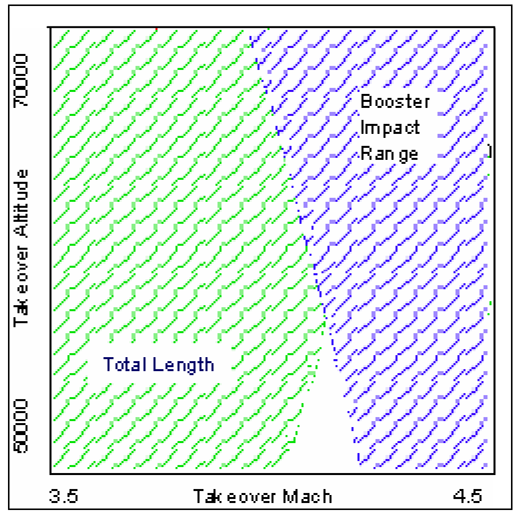

Figure 5: Booster/Ramjet Takeover Dynamic Tradeoff Environment

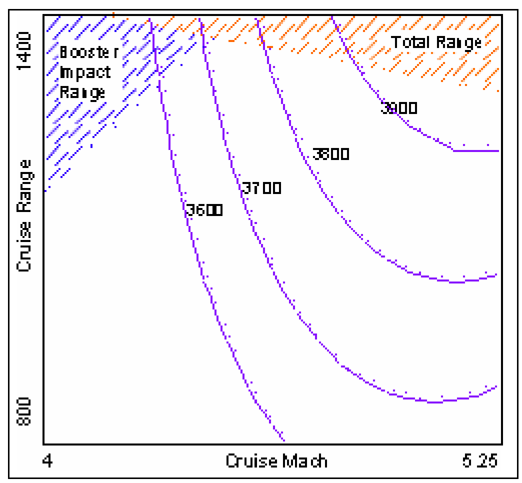

Figure 6: Cruise Segment Dynamic Tradeoff Environment

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 will diminish the feasible design space of the takeover condition, and 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.

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. Relative weightings, target values, and constraints are assigned to the responses. These desirability functions were used to find the optimized setting for each design variable.

The optimization used the metamodel to map the design variables to the system metrics so that the optimal point could be found almost instantaneously by maximizing total 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 effect of each design variable on the desirability of the entire system is shown in Figure 7.

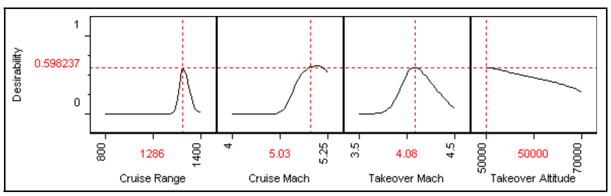

Figure 7: Desirability Curves for the Design Variables

To the size a missile that meets the optimized design mission parameters, the values for the design mission from the desirability curves in Figure 7 were used as the final inputs to the integrated environment in Figure 3. 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 metamodel. In addition, the metamodel 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.

The trajectory presented in Figure 8 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.

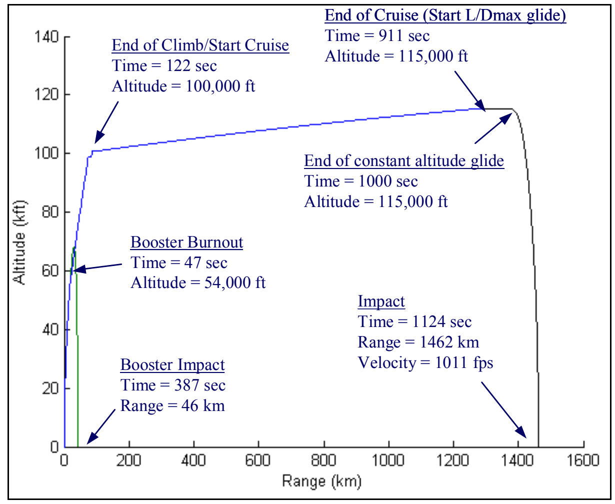

Figure 8: Maximum Range Mission Trajectory Profile

The layout presented in Figure 9 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.

Quantification of Uncertainty

Once the design point was selected, the uncertainty associated with that design point was quantified. The uncertainty analysis was limited to analyzing the effects of uncertainty in UNIX based disciplinary analyses on the sizing of the missile, driven by the inability to accurately measure the fidelity of those codes.

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 on the effects of lift, drag, I_{SP}, and thrust errors. This range was chosen to maintain the stability of the entire integration process.

The error factors were directly applied to the values used in the integrated sizing and synthesis environment. The sizing routine (trajectory, sizing, etc…) uses the drag polars and engine deck with the uncertainty factors already applied. A metamodel of the uncertainty environment was created so that a Monte Carlo analysis could be completed within a reasonable amount of time.

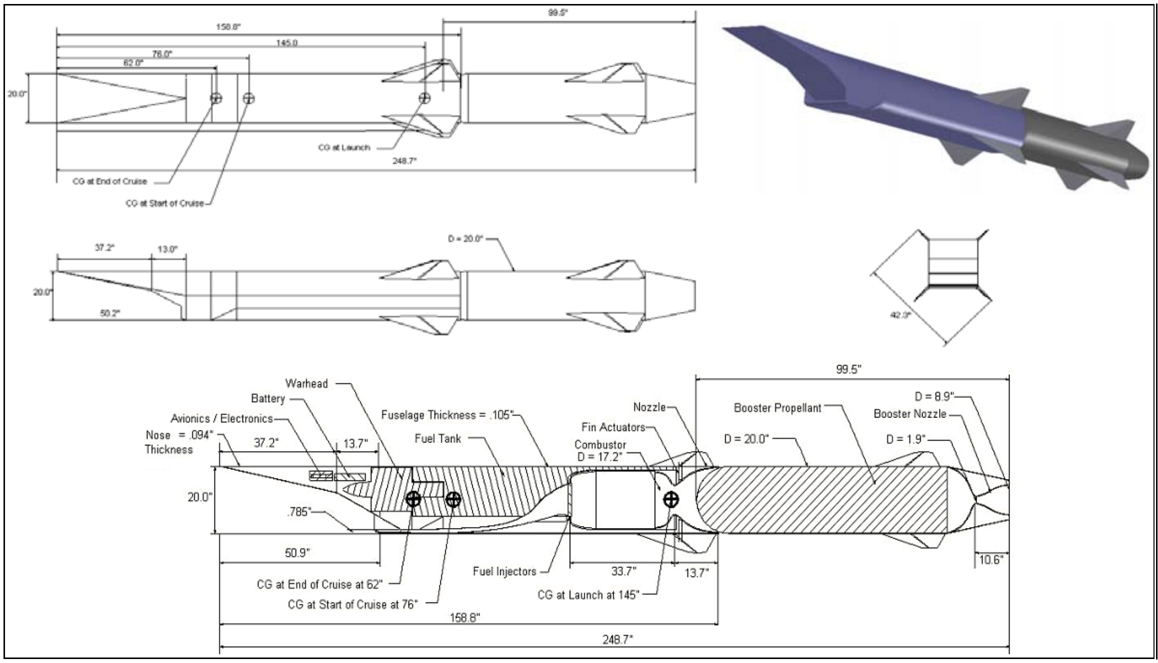

Figure 9: Hypersonic Cruise Missile Layout

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.

After running 10,000 cases, the values for launch weight 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.

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 7) could be altered by manipulating the OEC, and the uncertainty analysis rerun.

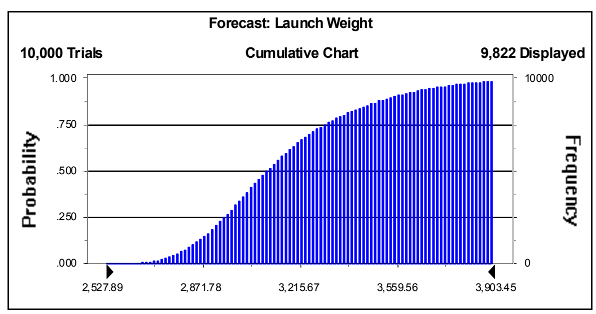

Figure 10: Cumulative Distribution Functions for Launch Weight

Conclusion

This study showed how the application of an advanced design methodology enhanced the conceptual design of a hypersonic standoff missile. Customer requirements were quantitatively reflected into the design, and were used to evaluate the overall system effectiveness of the final missile design.

Physics based tools were selected or created to analyze each discipline, relieving the designer from relying on a historical database. A parametric sizing and synthesis environment was created to integrate those disciplines.

A metamodel of this parametric environment allowed for a design space exploration that illustrated the tradeoffs between conflicting requirements. Using the customer weightings on the requirements, an optimization of the metamodel led to a near optimal design point. Once the design point was determined, the uncertainty associated with the design point was quantified. Depending on the customer satisfaction with the confidence levels associated with the particular design point selected, a new design point can be easily determined by manipulating the metamodel of the sizing environment, or changing the customer weightings used in the optimization.

Portions of this design methodology may have other applications as well. Entities that develop requirements could use the sizing environment presented in this paper 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.

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References

1 Centre for Defense and International Security Studies. “1990: The Iraqi Scud Threat”. http://www.cdiss.org/scudnt3.htm

2 Richard P. Hallion. “Storm Over Iraq”. Smithsonian Institution Press, Washington, 1992. Page 183.

3 Russel D. Shaver and Richard F. Mesic. “Calculating the Utility of Attacks Against Ballistic Missile Transporter-Erector-Launchers”. RAND, Santa Monica, CA.

4 United States Department of Defense. “Vertical Launching System” http://www.udlp.com/prod/vert_launch.htm

5 Kirby, M.R., Mavris, D.N., "A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment," SAE-2001-01-3018.

6 Dieter, G. E. Engineering Design: A Materials and Processing Approach. McGraw Hill Higher Education. 2000.

7 SAS Institute Inc., “JMP, Computer Program and Users Manual”, Cary NC, 1994

8 Fleeman, E. L. “Tactical Missile Design” American Institute of Aeronautics and Astronautics, Reston, VA 2001.

9 Burkardt, L.A., “RAMSCRAM - A Flexible Ramjet/Scramjet Engine Simulation Program,” NASA TM 102451

10 Gloudemans, J.R. and Paul Davis, “Rapid Aircraft Modeler (RAM)”, Developed by Sterling Software for NASA-Ames System Analysis Branch

11 Middleton, W.D., J.L. Lundry, R.G. Coleman, “A System for Aerodynamic Design and Analysis of Supersonic Aircraft” NASA Contractor Report 3352, 1980

12 McCullers, L. A. “AWAVE: User’s Guide for the Revised Wave Drag Analysis Program” ViGYAN, Inc., September 30, 1992

13 Burns, K. A., et. al. “Viscous Effects on Complex Configurations”, Technical Report WL-TR-95-3060, McDonnell Douglas Aerospace, 1995

14 Engineous Software, “iSIGHT” http://www.engineous.com/index.htm

15 Acrasoft, “Ground Control” http://www.acrasoft.com/gc.html