A PROBABILISTIC APPROACH TO UCAV ENGINE SIZING AIAA98-3264

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Abstract

This paper describes a probabilistic approach to aircraft engine thrust sizing which is intended to assist the designer in making decisions during the very early stages of the design process when the operational concept is still evolving and uncertainty abounds (in both mission requirements and technological capability). The focus of this paper is on analysis of mission uncertainty such as that due to ambiguity in payload, range, maneuver requirements, etc. and its impact on propulsion system sizing. Several analysis tools appropriate for probabilistic thrust sizing are discussed and one is applied to the probabilistic thrust sizing of an unmanned combat aerial vehicle designed for a deep-strike mission. The result is a distribution for thrust which can then be used in combination with the core engine design space to estimate the design's probability of successfully meeting the thrust requirements. Finally, a method for tracking mission uncertainty as the requirements develop is described and illustrated for the UCAV example.

Introduction

Historically, engine thrust sizing has been an evolutionary process wherein a set of design requirements steadily evolve over time to become a well-defined mission specification. However, since the maneuver and payload requirements placed on the aircraft are apt to fluctuate markedly as the requirements evolve, oftentimes the aircraft that emerges at the end of the production line is considerably different from the original sketches envisioned by the designer. This is especially the case when there is a midstream change in mission requirements, as has occurred in several recent aircraft design programs.

While fluctuations in design requirements are generally beneficial in arriving at the best possible system to meet future needs, it presents a serious programmatic problem to the engine manufacturer in the form of development lead time. Generally, the engine development time is longer than that of the aircraft itself. It therefore follows that in order to field the best possible system with a reasonably short development time (and therefore least cost), it is necessary for the engine manufacturer to have an accurate estimate of engine thrust required so that engine design and development can begin. Additionally, it is important for the engine manufacturer to know the mission profile for engine cycle optimization, and aircraft growth scenario for selection of core size.

Unfortunately, fluctuations in design requirements prevent exact specification of the true design requirements until later in the design cycle and also have an adverse impact in terms of engine development time and cost due to redesign and hardware re-work. This study seeks to minimize the impact of these fluctuations via probabilistic techniques as applied to engine thrust sizing during the very early stages of design. Ideally, this would be applied concurrently with engine cycle optimization to arrive at a propulsion system design with the highest possible probability of success. However, in the interest of brevity, this paper will focus exclusively on the thrust sizing problem and assume that the cycle is already tailored for the mission.

The probabilistic approach employed here addresses the inherent uncertainty in vehicle mission requirements in an analytical and rational manner by representing payload, mission, and maneuver requirements as probability distributions instead of point values. For example, the probabilistic approach would allow one to specify a sustained turn requirement at combat weight in terms of a probability distribution of g-loadings instead of forcing the designer to specify a 5-g sustained turn requirement. This results in a probability distribution for aircraft thrust loading, takeoff gross weight, and engine size rather than a point value, as is usually the case. It then becomes a simple matter to specify an acceptable probability of meeting or exceeding the thrust requirements (one might, for example, want to be assured of having at least a 90% probability of meeting or exceeding the vehicle thrust requirements when developing a derivative engine from an existing core).

This type of probabilistic approach has several advantages over deterministic methods, the chief of which is the fact that it provides an analytical basis for decision-making in the presence of uncertainty. This is critical during the very early stages of program

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development where design choices can have a drastic impact on the success or failure of the program. Moreover, the probabilistic technique illustrated herein is flexible and simple enough to be used for "what-if" scenarios as well as uncertainty tracking as the requirements develop.

The discussion begins with a review of basic thrust sizing methods, and this is subsequently extended to probabilistic thrust sizing. Additionally, several probabilistic analysis tools suitable for thrust sizing are discussed, and a brief discussion of when and how to apply them is offered. The probabilistic method is then applied to the sizing of an unmanned combat aerial vehicle (UCAV) aircraft and propulsion system.

Classical Thrust Sizing

The thrust required for a given aircraft is a function of the thrust loading and takeoff gross weight (TOGW). The simplest way to estimate TOGW (denoted as W) is to decompose it into a sum of major group weights and express these group weights as non-dimensional group weight fractions:

$$W=W_{PL}+W_S+W_{FEQ}+W_P+W_F \qquad (1)$$

where the subscripts correspond to payload, structural, fixed equipment, and propulsion system weights, respectively. An equivalent expression is:

$$1=\frac{W_{PL}}{W}+\frac{W_S}{W}+\frac{W_{FEQ}}{W}+\frac{W_{PR}}{W}+\frac{W_F}{W} \qquad (2)$$

These weight fractions are in turn dependent on available technology as well as mission and maneuver requirements. If the technology level is assumed to be fixed, the problem is reduced to a matter of finding the values for the weight fractions given in equation (2). Since it is assumed that the payload weight is known, equation (2) can be re-arranged to express the payload weight fraction as a function of the fuel, propulsive, and structural weight fractions. Fuel weight fraction can be estimated with relatively good accuracy by analytically "flying the mission" via piecewise integration of the Breguet range equation:

$$dR=\frac{-dW}{W}\left(\frac{{}^{L}\!/\!{}_{D}\,V}{SFC}\right) \qquad (3)$$

where R is range, W is instantaneous weight, v is flight velocity, L/D is lift-to-drag ratio, and SFC is engine specific fuel consumption. The result is the fuel fraction required to complete the mission.

Unfortunately, there are no analogous "physics-based" equations which can be used to accurately estimate the structural and propulsive weight fractions of a particular aircraft at the conceptual design level. Instead, these figures of merit are usually selected based upon historical data and the designer's best guess as to the capabilities of current technology. Once the weight fractions have been determined, it is then a trivial matter to calculate the payload weight fraction, and thence, the design takeoff gross weight.

The second element in thrust sizing is determination of the thrust loading required to perform the critical maneuver(s) specified in the mission requirements. This is typically done using a carpet plot or a sizing plot, an example of which is shown in Figure 2. The sizing plot is effectively a representation of the normal and tangential acceleration capability provided by the wing and engine respectively[1]. In general, using the smallest engine and wing will provide the solution with lowest acquisition cost (though not necessarily the lowest life cycle cost), so it is therefore desirable to find the point with the highest wing loading and lowest thrust loading possible while still satisfying the maneuver requirements (the sizing point). This is found by expressing the maneuver requirements in terms of thrust & wing loading and plotting these on the sizing plot as shown in Figure 2. This divides the design space into a feasible and a non-feasible region and it is then a simple matter to pick the most economical solution to the requirements. Once the sizing point is determined, the thrust loading for the aircraft is known and the engine can be sized appropriately.

At this point, the design is now defined well enough for the engine manufacturer to begin the preliminary design process. Once core size is fixed (core being the high pressure compressor, combustor, and high pressure turbine), fluctuations in the engine thrust requirements can be compensated for via compromises in engine cycle. However, if the thrust requirement deviates too far from the original sizing point, the engine manufacturer will be forced to re-design the entire engine to meet the new thrust goal. The advanced tactical fighter program is a case in point wherein aircraft weight gain late in the design program forced one engine manufacturer to re-design and the other to fly the demonstrator with a sub-scale engine. Obviously, the engine manufacturer would like to select the core size appropriately the first time and thereby avoid the expense and time needed to re-design the entire engine, and this is one of the main objectives which the probabilistic method seeks to address.

Probabilistic Thrust Sizing

The primary difference between classical and probabilistic thrust sizing is that the latter represents uncertain parameters as a distribution instead of a point value. This includes uncertainty in 1) *mission and maneuver requirements* as well as 2) *technological metrics* such as structural weight fraction, propulsion weight fraction, L/D, or cruise SFC, as shown in

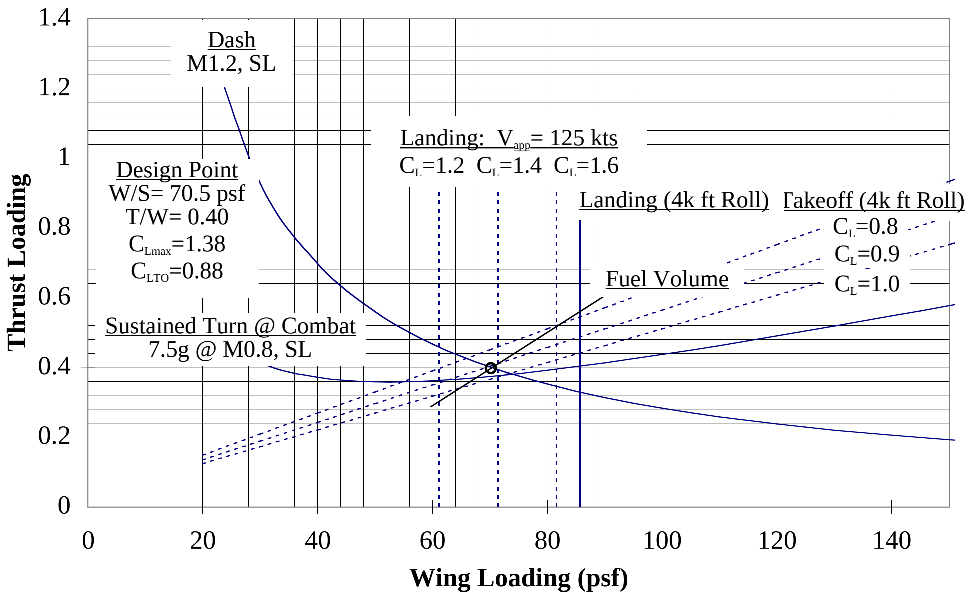

Figure 2: Typical Fixed-Wing Aircraft Design Plot

Figure 1. These distributions are then be used as inputs to the sizing process and the result is a distribution for engine size instead of a point value. This paper focuses on the application of probabilistic engine sizing methods as a means to account for *mission uncertainty*. The topic of technological uncertainty is mentioned only in passing and is the subject of future work.

The most important requirement for accurate and realistic use of probabilistic thrust sizing methods is an understanding of the underlying probability and statistical concepts which are the foundation of these techniques. Specifically, one must have answers to such questions as:

- When is it appropriate to apply probabilistic methods?
- What probabilistic analysis tools are available?
- How should distributions and ranges be selected?
- How should the results be interpreted?

This paper endeavors to provide some answers to these questions via the discussion of this section and subsequent application to a UCAV system.

The answer to the first question posed above is obvious. Probabilistic methods should be applied whenever there is sufficient uncertainty to cause a significant distribution range in the response. Of course, “significant” is a subjective term and it is the relative sensitivity to variation that ultimately drives the decision as to whether probabilistic techniques are warranted. For instance, the UCAV lends itself to probabilistic analysis due to the large uncertainties in mission requirements. However, the Joint Strike Fighter program currently has a well-defined mission with little ambiguity, and therefore stands to gain little from analysis of mission uncertainty (but note that, as of the time of writing, there is considerable technological uncertainty yet remaining!).

Probabilistic Analysis Tools

The second question posed above requires more depth of explanation than the first. There are currently several obstacles impeding the implementation of probabilistic sizing methods, the most obvious being the fact that all of the sizing codes currently in existence are deterministic in nature and do not allow variables to be represented as a distribution. Fortunately, recent advances in numerical probabilistic methods and tools have emerged to remedy this problem, and are now sufficiently developed as to constitute a well-rounded

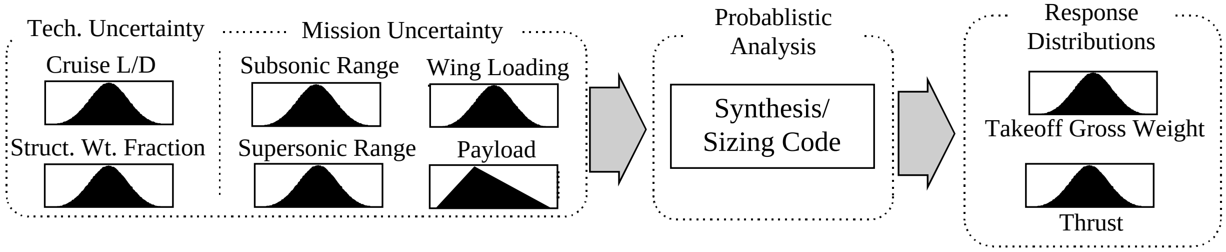

Figure 1: Probabilistic Engine Thrust Sizing

suite of tools available for the designer to use in the analysis process. Although there are many techniques available, only four of the most popular will be described here.

The simplest and least mathematically rigorous probabilistic analysis tool is the orthogonal array method suggested by Taguchi[2]. This technique attempts to estimate the effect of uncertainty by perturbing the uncertain parameters in some specified way and looking at the cumulative effect of these variables on the response via calculation of the signal-to-noise ratio in the resulting data set. This technique is very simple and easy to implement, but is far from being mathematically rigorous and is therefore appropriate when speed (but not accuracy) is the objective. It is therefore of limited usefulness for probabilistic thrust sizing where the objective is to obtain an accurate estimate of the thrust distribution.

The antithesis to the orthogonal array technique is Monte Carlo simulation because it is the most accurate method to do probabilistic analysis. Monte Carlo simulation employs a random number generator to select random values for each input parameter based on the input distributions and sorts the result into bins, repeating this procedure thousands of times. As each result is sorted into the appropriate bin, the result is a frequency distribution for the response. This method is quick and simple to use if it is applied to a spreadsheet analysis or a simple computer program. However, this method is not practical if the function evaluation is costly or time consuming, as is usually the case for aircraft sizing routines.

As a compromise between the previous methods, a third tool gaining popularity are RSMonte techniques in which response surface methods (RSM)[3] are combined with Monte Carlo by using RSM to create a response surface equation (RSE) which captures the essence of the complicated analysis code. This RSE is then used in conjunction with Monte Carlo techniques to obtain a resultant distribution[4]. The accuracy of this method is heavily dependent on the accuracy of the RSE in representing the behavior of the code being modeled[5]. If the analysis code is well-behaved (i.e. produces results which are smooth and continuous), this technique can give accurate results with minimal effort, as will be shown in the forthcoming UCAV example.

A fourth technique which shows a great deal of promise in overcoming the limitations of all of the above techniques is the fast probability integration method (FPI). This is a mathematically rigorous technique which allows accurate evaluation of probability distributions based on only a few function calls[6]. This technique has been in use for years in the field of reliability analysis and is now being explored for use in aerospace systems design applications. The theory behind this technique is beyond the scope of the present discussion, but suffice it to say that the underlying principles of this technique are well-understood. Since FPI has both speed and accuracy, it is appropriate for most problems in probabilistic analysis, including probabilistic thrust sizing.

The relative accuracy and computational efficiency of these four methods are compiled in Table 1. In summary, the orthogonal array method is the least accurate and simplest to implement, while Monte Carlo is the most accurate and least efficient. The RSMonte and FPI techniques lie somewhere in between with the former having the advantage of being easily modified and re-computed while the latter has an advantage in accuracy and speed.

Assumption Distribution Selection

The method by which the input distributions are selected will have a large impact on the resultant distribution. This implies that it is important to select the input distributions as accurately and consistently as possible in order to have a reasonable analysis.

The first step in defining assumption distributions is to select the most likely point for each input variable. These are typically established based upon design experience or historical data and are usually fairly easy to estimate. If a database of historical data is available which contains several data points (as for a collection of similar aircraft), it may be appropriate to simply take the arithmetic average of the data set for use as the mean. Oftentimes, it is necessary to apply a delta to historical data to account for changes in requirements or new technology since historical data is, by definition, agéd. Unfortunately, only experience and common sense are available to guide the designer in appropriate estimation of these effects.

Estimation of variance is somewhat more complicated than that of means. The quickest but least rigorous way to determine variance for an uncertain parameter is to simply select an upper and lower bound based upon design experience and assign these the 2nd and 98th percentiles of the distribution. Obviously, since the 2nd and 98th percentiles lie two standard deviations away from the mean (assuming a normal distribution) these values should be equal to the highest

Table 1: Summary of Probabilistic Analysis Techniques

Method	**Accuracy**	**Efficiency**
Orth. Array	Low	High
Monte Carlo	High	Low
RSMonte	Medium	Medium
FPI	High	High

and lowest that would reasonably be expected to possibly occur in the final design (i.e.- the chances of actually achieving the upper or lower limit is a long shot).

A more rigorous way to determine variance is to use a set of historical data to calculate the variance of the population, analogously to the calculation of mean described earlier. Historical data is also useful for determining the type of distribution to be used (normal, triangular, uniform, beta, weibul, etc.). Since there are numerous treatises which discus these distributions, their use, and the theory behind them, the interested reader is referred to ref. 7 for an introductory discussion on this topic.

Interpretation of Results

There are two distinct approaches to interpretation of probabilistic results: 1) maximizing the probability of success (probabilistic design), and 2) minimization of variance about a target value (robust design). An example of a robust design problem is the measurement of design point thrust for a population of engines all coming off the same production line. Although the engines are identical in design, there will generally be some variance in the design point thrust due to manufacturing variations. The objective of the engine manufacturer is to minimize the variance about the design thrust, and one way to do this is to make design changes which minimize the sensitivity of engine thrust to manufacturing variations via robust design.

On the other hand, if the engine manufacturer must guarantee a rated thrust, it is necessary to design in a thrust margin to accommodate the variance in thrust from engine to engine. However, excessive thrust margin is wasteful, so the objective of the engine manufacturer is to find a thrust margin large enough to guarantee that 99.5% (for example) of all engines produced meet or exceed rated thrust. This is essentially a probabilistic design problem, as the objective is purely probability of success with no concern for minimization of variance.

In the context of thrust sizing, the objective is to select an engine size for a given cycle such that the probability of meeting the final thrust requirement is maximized with minimal compromise in cycle. This is achieved by finding a probability distribution for thrust required which, in combination with the range of thrusts achievable in the core design space, yields an overall probability of meeting the thrust requirement.

UCAV Probabilistic Thrust Sizing

The topic of Unmanned Combat Aerial Vehicles has received a great deal of interest as of late, primarily because of the UCAV's potential to reduce the cost of operations by 60 to 70% over current aircraft while maintaining comparable capability levels. However, UCAVs are currently in the very early stages of development and there is no clear definition of what the capabilities must be in terms of payload, range, maneuverability, technology, etc. This problem is compounded by the fact that the service requirements are not static, but continue to evolve over time. The net result is that the uncertainty in design requirements is making it difficult for any airframer or engine manufacturer to spend significant sums of money in the development of these concepts without direct Department of Defense sponsorship due to the risks involved.

This is especially true for the engine manufacturers in that there does not appear to be an off-the-shelf engine well suited to the requirements, yet engine manufacturers are unwilling to spend the money necessary to begin the long lead-time development process because of the high probability that the engine they start developing will not be the thrust class or cycle required for the final vehicle.

In order to address these problems, General Electric Aircraft Engines, Evendale OH, and the Aerospace Systems Design Laboratory at Georgia Tech are working on several joint studies aimed at developing methods for analytically treating uncertainty in the design process. This study is the culmination of one such project applied to probabilistic thrust sizing of UCAV engines. For the purposes of this discussion, it is assumed that the engine cycle is tailored to suit the mission needs and is therefore considered to be fixed.

Baseline Vehicle

The first step is to design a vehicle to meet the best estimate of the current vehicle requirements. This vehicle serves as a baseline from which to conduct the uncertainty analysis. The obvious missions for a first-generation UCAV are deep strike of fixed targets and suppression of enemy air defense (SEAD) missions because these are hazardous and do not require complex maneuvering or control decisions such as are required for maneuvering air combat. Thus, the design mission selected for this study is a hi-lo-lo-hi deep penetration strike with a 400 nmi radius as shown in Figure 3. The combat radius requirement was selected based on similarity to the capabilities of current systems.

The hi-lo-lo-hi mission profile shown is a result of the basic design philosophy adopted here, that being that the use of high-speed, low-level penetration in conjunction with stealth shaping and hiding (but *not* treatments) will provide the greatest possible survivability in the face of an ever-changing threat environment. Additionally, the supersonic vehicle has a

Leg	Description	Leg	Description
0-1	Warm-up, Taxi, Takeoff	6-7	Supersonic Dash 50 nmi to Escape
1-2	Climb to BCA	7-8	Climb to BCA and Decelerate
2-3	Cruise 350 nmi at BCM	8-9	Cruise 350 nmi at BCM
3-4	Descend to 1k ft, Accel to M1.2	9-10	Descend (no range credit)
4-5	Supersonic Dash 50 nmi to Target	10-11	Land w/ 5% Reserve, 1% Trapped
5-6	Weap. Release, 7.5g Escape Man.		

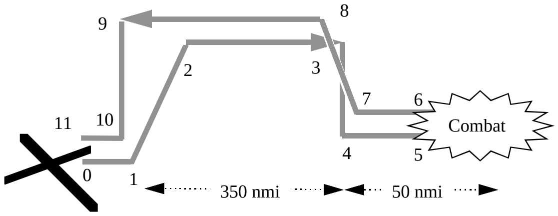

Figure 3: Baseline UCAV Deep Strike Mission

Table 2: Vehicle Mission Requirements

Payload:	2 - 1145 lb JDAM
Range:	800 nmi Total, 100 nmi Supersonic/Low Altitude
Performance:	7.5g Sustained Turn @ Combat Weight/SL 300 fpm P_s @ Dash 120 kt Approach Speed
Ferry Range:	> 3,000 nmi
TO/Land:	Conventional, < 5,000 ft
Vehicle Life:	200 Missions (800 hrs)
Sensors:	Minimal/BDA Only
Storage:	Long Term, Near Mission-Ready

superior payload productivity (mission block time*payload), and is generally a much more growth-capable vehicle due to the higher thrust loading. The use of treatments is avoided as a means of self-preservation due to:

- Expense of coatings
- Uncertainty of ensuring coating effectiveness after long-term storage
- The fact that UCAV units will likely be staffed by skeleton crews which lack sufficient manpower to maintain coatings during times of continuous deployment (a la Persian Gulf)
- Difficulty in ensuring coating effectiveness when assembled from crated transport configuration

Further mission requirements are enumerated in Table 2, all of which are based on mission requirements typical of deep-strike aircraft, with the exception of the airframe life requirements. Note also that the primary weapon is the 1,000 lb JDAM munition, but the vehicle is assumed to be capable of carrying any weapon of comparable weight which will fit inside the weapon bays (which were sized to accommodate a folding-fin HARM missile).

The aircraft that emerged from these requirements is shown in Figure 4, with the internal layout depicted in Figure 5. Note that the design features two internal weapons bays, a top-mounted inlet, and a v-tail for reduced signatures. Additionally, two wing hardpoints, conventional takeoff/landing, a 3,000+ nmi ferry range, and a top speed of Mach 1.3 give this vehicle a great deal of operational flexibility. Finally, a $9.4M unit flyaway production price gives a very affordable vehicle costing approximately 61% less in terms of fleet life cycle cost as compared to a fleet containing the same number of F-16As (the caveat being that the capabilities of the two are not the same).

As mentioned previously, the vehicle weight and internal volume are sized for the 800 nmi HLLH mission. The engine is sized for 300 fpm P_s at M1.2, 1000 ft altitude so that it has the ability to perform gentle turns without loosing speed or altitude. The wing size is driven by fuel volume and field length constraints, and easily meets the combat maneuver requirement as shown in the sizing plot of Figure 2. Other major attributes of this vehicle are summarized in Table 3.

Table 3: Basic Vehicle Attributes

TOGW	16,624 lb
F_N(lb)	6,638
T/W	0.40
W/S	70 psf
S	237 ft^2
C_{Lmax}	1.4
AR	3.0
Λ_{LE}	49 deg
OEW	8767 lbs

Assumption Distribution Selection

The establishment of this baseline "most likely" design sets the stage for the probabilistic thrust sizing analysis. Obviously, the first (and most important) step in this analysis is to determine which parameters are uncertain and set bounds on the uncertainty. In this case, the uncertain parameters of interest are obvious: vehicle payload, range (both sub- and supersonic), and maneuver requirement.

It also seems sensible to include the dash Mach number as an uncertainty since it has such a profound

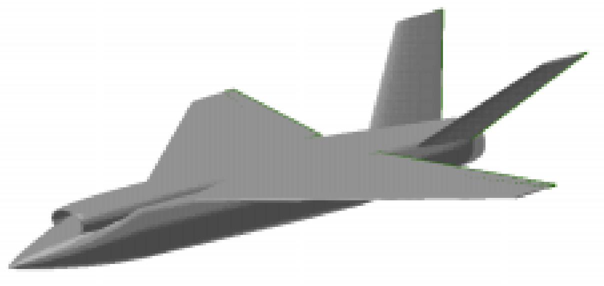

Figure 4: Baseline UCAV Configuration

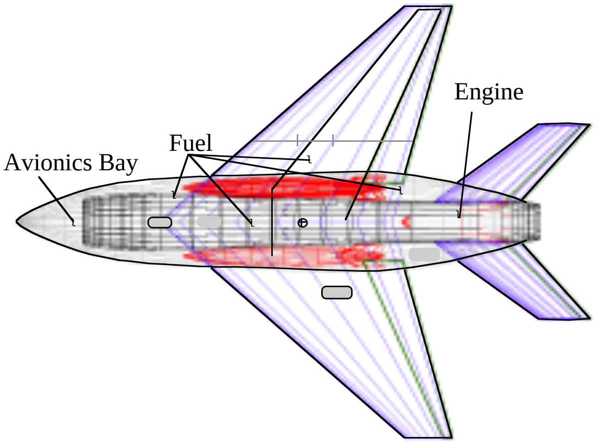

Figure 5: Baseline UCAV Internal Layout

impact on the vehicle size and thrust required. However, the low altitude dash is so intrinsic to the survivability of the vehicle that any decrease would make the vehicle extremely vulnerable to attack. Conversely, increasing the dash Mach number gives an exponential increase in sized vehicle weight and cost as shown in Figure 7, thereby negating the primary advantage of the UCAV over piloted systems. Therefore, the range of dash Mach numbers is narrow enough to warrant fixing it at M1.2 for the purposes of this study and treating it as one of the fundamental study assumptions.

Next, ranges are selected for each of the uncertain parameters, starting with payload. The most likely payload for a UCAV vehicle is two 1,145 lb JDAM-type munitions. Heavier payloads become increasingly improbable because the resultant vehicle quickly grows into a weight class comparable to manned systems. It is not likely that one could develop, procure, and operate such a large UCAV system for less expense than that required to upgrade existing (manned) systems, so the upper limit on UCAV payload is taken to be 4,000 lbs. As for the lower bound on payload weight, it is conceivable that a payload on the order of only 1,000 lbs could be required, especially if new “mini-munitions” are developed for use with UCAV vehicles, so this value is taken as the lower bound on payload weight. This yields a realistic distribution for payload weight based on common sense and design experience as shown in Figure 6.

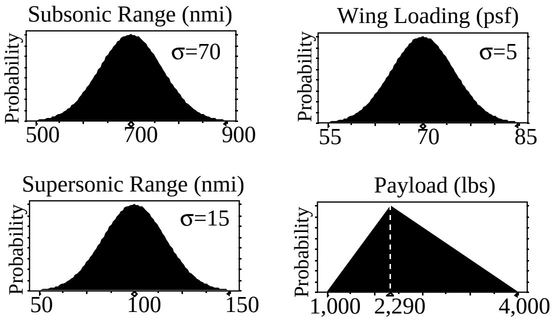

Figure 6: Parameter Range Distributions

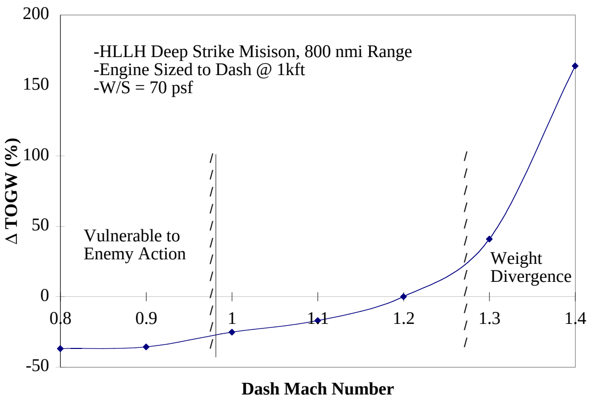

Figure 7: Sized Vehicle Gross Weight vs Dash Mach Number

The distribution for design range is selected in an analogous manner, except in this case, the mean and variance are defined based on historical data. Specifically, the radius of action for several current aircraft were compiled, so assuming that the range requirement will not change drastically in the future, this gives a reasonable idea of what the mean and standard deviation for vehicle range should be. In order to determine the split between subsonic and supersonic range, the best method would be to conduct a detailed assessment of likely threat environments to determine what percent of the distance the vehicle will be required to fly in a high threat environment. However, the resources available for this study did not permit this type of detail, so the supersonic range was again selected based on design experience.

The distributions selected are shown in Figure 6 for subsonic and supersonic range. Note that the maximum vehicle range is 1,050 nmi while the minimum range is 550 nmi. Furthermore, the minimum supersonic range is taken to be 50 nmi instead of zero nmi because the assumption of supersonic capability is intrinsic to the baseline UCAV concept. The lack of supersonic capability implies a stealthy design, and the overall vehicle layout will change considerably (the baseline concept would no longer be valid). As a result, it would be inconsistent to consider a zero length supersonic segment in this study. A better approach is to create a stealthy subsonic design and conduct an analogous probabilistic analysis on that vehicle.

The final distribution to be estimated is that due to the escape-maneuver requirement at combat weight. The purpose of this requirement is to ensure that the vehicle has reasonably good maneuver capability during combat when it is likely to be needed most. There are numerous possible maneuver constraints for this type of aircraft (sustained turn, instantaneous turn, acceleration, excess thrust, etc.) and it would be cumbersome to assign separate distributions to every possible maneuver requirement. A better approach is to assign a distribution to the wing loading directly, implicitly capturing the effect of the wing-sizing maneuver requirements on the vehicle. Since the engine sizing requirement is essentially fixed by the dash maneuver, the result is an implicit distribution on thrust loading due to the wing loading distribution, as shown in Figure 8. Thus, the myriad of possible maneuver requirements are reduced to a matter of picking a distribution for wing loading.

The mean value for wing loading is driven by field length and fuel volume requirements. Any wing loading significantly greater than 70 psf will result in unacceptable field length while anything less results in an unacceptably heavy aircraft. Thus, the upper limit for wing loading is that which gives marginally acceptable field performance, while the lower limit on wing loading is set by divergence of sized vehicle gross weight and historical precedent. Since these values effectively serve as upper and lower limits on feasible solutions, they are assumed to be at the 5% and 95% probability levels, respectively (i.e. ±2 standard deviations from the mean). The distributions for all four parameters are summarized in Figure 6. The basic effect of each distribution on vehicle attributes is shown in Figure 8.

Analysis Method and Results

The last prerequisite to probabilistic sizing is the selection of the analysis method to be used. The previous section described four techniques, each of which has its own strengths and weaknesses. Based on the requirements of the current analysis, the RSMonte method is the most appropriate for several reasons:

- Extreme accuracy is not required (therefore FPI and Monte Carlo are unnecessary)
- However, it is desirable to mathematically estimate the probability levels (therefore, inner/outer array method is not appropriate)
- It is desirable to have a response surface representation for thrust and gross weight so that the probability distributions can easily be modified and recalculated if so desired at a later date

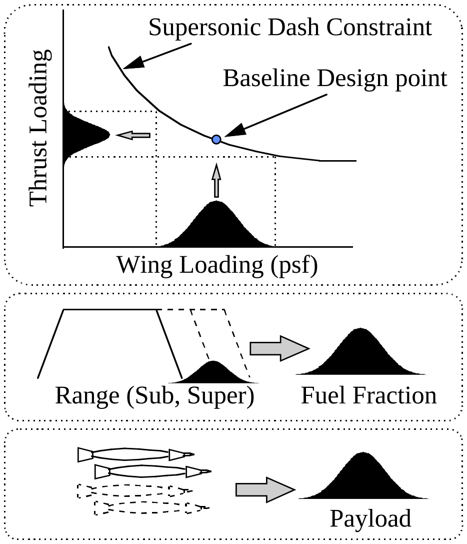

Figure 8: Distribution Effect on Vehicle Attributes

The probabilistic analysis method used is schematically outlined in Figure 9. The first step is to construct RSEs for takeoff gross weight and thrust using response surface techniques. These response surfaces are then used in conjunction with a Monte Carlo simulator to estimate distributions for TOGW and thrust.

RSE construction required the execution of 25 sizing cases using a 4 factor central composite design. The central composite design was selected because it provides good experimental fidelity, yet has a manageable number of cases for a 4-factor design. The resulting RSEs have a correlation coefficient of 96% for thrust and 96% for TOGW, and both do a good job of estimating TOGW and thrust as a function of subsonic range, supersonic range, payload, and wing loading. A byproduct of RSE generation is the Pareto plot for engine thrust shown in Figure 10 which gives the magnitude of the contribution from each variable and interaction. Note that the wing loading and the supersonic dash range are the primary factors in defining engine thrust requirements, with these two variables and their interactions constituting 64% of the thrust response. The single most important factor is the interaction of wing loading with supersonic dash range, which contributes 18% of the total response.

Another useful figure which can be generated from the RSE data are the trend plots for thrust and TOGW shown in Figure 11. These plots show the deltas in gross weight and engine thrust as a function of a percent delta in mission and maneuver requirements. The trends given in this figure show wing loading to have the most influence on both thrust and weight while

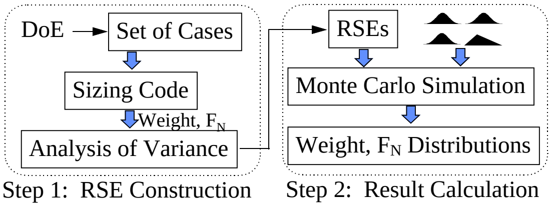

Figure 9: Analysis Method Flowchart

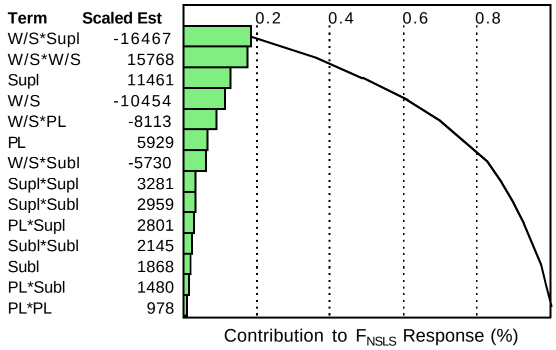

Figure 10: Pareto Plot for Sea Level Standard Net Thrust

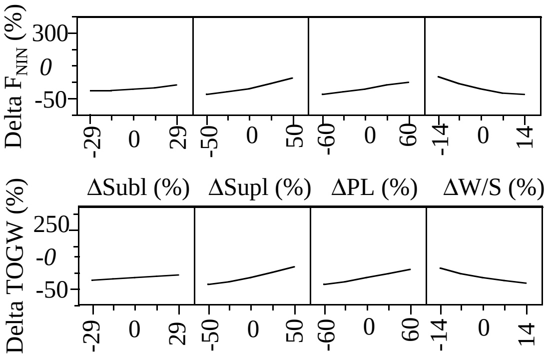

Figure 11: TOGW and Thrust Trends

subsonic range is the least influential. Note also that the upper and lower values shown on the y-axis are the maximum and minimum deltas encountered in the RSE data set, which means that by suitable perturbation of the mission parameters within their defined ranges, it is possible to get thrust requirements as low as -50% and as high as 300% of the baseline configuration. In point of fact, the sizing cases which yielded these large thrust deltas from the baseline will be somewhat inconsistent due to the fact that the large change in thrust implies a significant change engine diameter and, therefore, wave drag (which was not accounted for in the analysis). However, the trends are correct, and these two figures taken together provide a very graphical view of the magnitude and direction of the thrust trends as a function of the mission parameters.

The next step is to use Monte Carlo simulation to get a distribution for thrust based on the mission uncertainties defined earlier. The thrust sizing results of the Monte Carlo analysis are shown in Figure 12, in the form of frequency and cumulative probability distributions. Note that the mean thrust is 8,239 lbs with a standard deviation of 2,689 lbs. It is clear from the frequency plot that the distribution for thrust is skewed towards the lower values, which implies that if one has the option to select a baseline engine thrust, the best choice would be on the lower side of the mean at approximately 8,000 lbs thrust. The results also indicate that there is roughly an 80% probability that the engine thrust will be less than 10,250 lb (afterburning), but only a 21% chance that the thrust will be less than 6,000 lbs.

<u>Engine Selection Scenarios</u>

There are several options available in selecting an engine for the UCAV mission under consideration. The first option is to determine if there are any existing engines in an appropriate size and cycle regime to meet the requirements. Perusal of current production engines quickly reveals that the closest match is the Rolls Royce Adour (6,900-8,500 lb thrust). If this thrust range is superimposed on the cumulative distribution of Figure 12, one can see that the Adour has, *at best*, a 35% probability of meeting the thrust requirement, though the actual probability will be somewhat less due to the fact that the cycle is not well-matched to the mission (implying a fuel burn penalty). Note that the probability of success for an F404 thrust-class engine (16,000 lb) is nearly zero. Therefore, the UCAV mission investigated here demands a thrust class and cycle combination that is essentially *non-existent* in today's gas turbine engine market.

The second option is to investigate the possibility of using a derivative engine based on an existing core. There are several engine manufacturers having current-production cores that could theoretically be adapted for the supersonic mission, and it is a straightforward exercise to estimate the thrust design space (thrust band) available in each derivative at the fan pressure ratio used in the baseline engine. However, it would be far too lengthy to discuss all of the scenarios here, and the

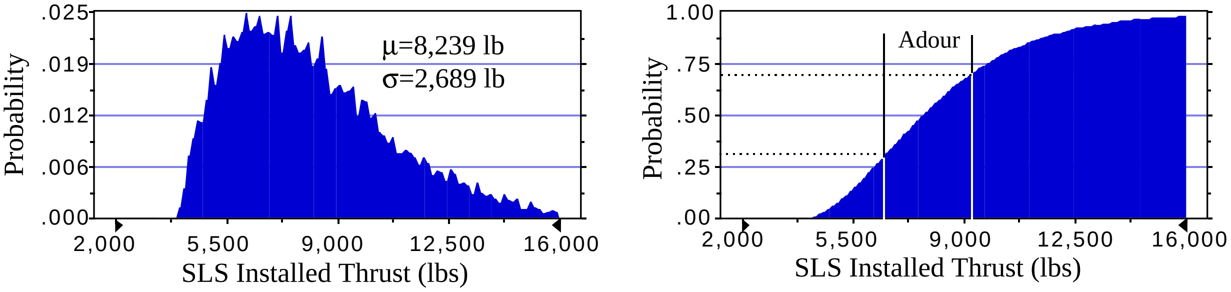

Figure 12: Frequency and Cumulative Distributions for UCAV Thrust

authors will instead simply comment that the outlook for creating well-matched propulsion systems is considerably better for this option than for the “existing engine” option.

The final option is to use a “new centerline” engine. The objective here is to ensure that the baseline core design has a broad thrust band in order to maximize the probability of meeting the final thrust requirement. The width of this thrust band is typically dictated by core size, relative RPM margin, T3 margin, and T4 margin, and an increase in any of these margins will generally result in a higher probability of success (at the risk of having a core engine that is heavier and more expensive than necessary). Thus, the crux of the problem is to achieve the best balance between weight and probability of success.

Once the core size and design margins are set, it is possible to estimate the thrust band for that core configuration. Usually, this is accomplished by increasing inlet mass flow at the expense of fan pressure ratio (FPR) and engine diameter. Increasing inlet mass flow is an effective way to tailor thrust until the losses associated with the increased flow impose an unacceptably large penalty in cruise SFC, at which point it is necessary to re-size the core (an undesirable proposition once a test core has been committed to hardware). A simple way to obtain a first-pass estimate for allowable thrust range for a given core configuration is to do a sweep of fan pressure ratio while holding core size constant and allowing inlet mass flow to vary. A plot of change in SFC and engine diameter from the baseline values vs thrust will quickly reveal what the acceptable limits for thrust are, and this thrust band can be superimposed on the distribution of Figure 12 to estimate probability of success, just as was done previously.

<u>Mission Uncertainty Tracking</u>

The probabilistic method espoused here is useful even after the baseline core size has been selected because it facilitates tracking of the mission uncertainty as it evolves over time. One very likely scenario for a UCAV is the development of new “mini-munitions” which would have the same destructive power as their conventional counterparts, but take less volume and weight. In this case, the 2-JDAM payload is still highly probable, but payloads significantly in excess of this become highly unlikely. Furthermore, payloads less than 1,000 lb become more likely than before. A reasonable payload distribution based on this scenario would be to set the lower limit at 800 lbs and truncate all probabilities greater than 2,290 lb so that the distribution looks like the right triangle on the left side of the dashed line in Figure 6, while all other distribution assumptions remain as before.

It is then a simple matter to re-run the Monte Carlo simulation to obtain the results shown in Figure 13. The thrust class with the highest probability of success for this case is roughly 6,500 lbs. Note that in this scenario, the Adour’s probability of success is 33%. Interestingly, this yields a vehicle that is beginning to move into the J85 thrust class, as illustrated by the 19% probability of success for this engine (but recall that the cycle is not matched).

This approach is not limited to thrust sizing only, but can also be used to obtain distributions for wing size, fuel weight, TOGW, etc. The distribution for TOGW for the above scenario is shown in Figure 14. Note that the mean TOGW for this vehicle is 14,903 lb and the standard deviation is 3,124 lb. Not surprisingly, this indicates that the baseline vehicle selected for this study is heavier than the actual vehicle would likely be under the “mini-munition” assumption. Additionally, the standard deviation indicates that there is a 68% probability that the vehicle TOGW will lie in the range 11,800<TOGW<18,000 lbs.

Up to this point, this paper has focused exclusively on thrust sizing for a UCAV which uses a combination of supersonic, low altitude penetration and stealth as its means of defense. However, there is another design philosophy which advocates the use of stealth as the primary means of defense. In order to have a complete picture of the UCAV engine sizing outlook, it is necessary to conduct a complementary probabilistic thrust sizing study for a family of stealth designs.

The authors expect that it is very likely that the stealth family of designs will require much less thrust

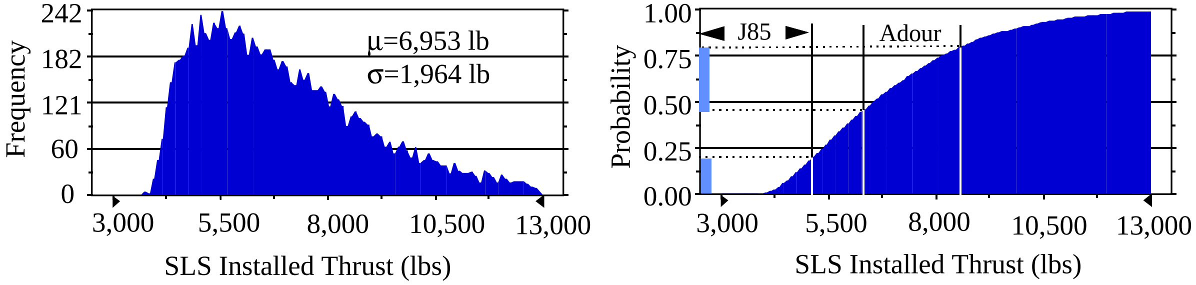

Figure 13: UCAV Thrust Distribution for Reduced Payload Scenario

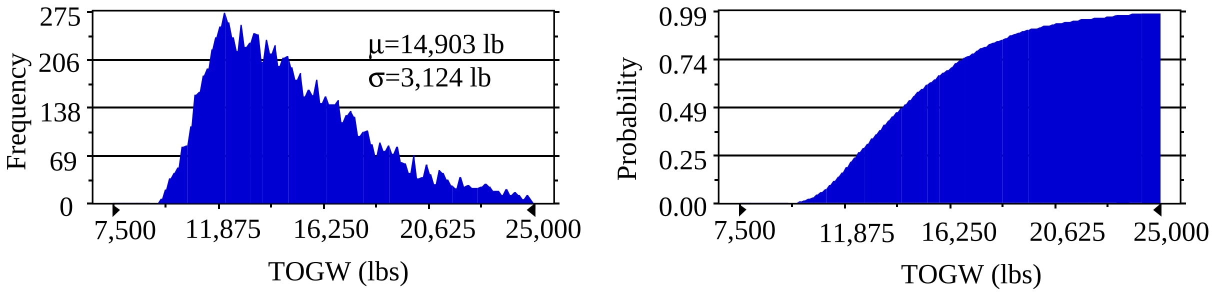

Figure 14: Cumulative and Frequency Distributions for UCAV TOGW

than the supersonic vehicle (perhaps on the order of 5-6,000 lbs). On the surface, this seems quite different from the 8,000 lb thrust class demanded by the supersonic vehicles. However, use of an afterburner on a subsonic stealth vehicle is probably not a viable option, thus implying that the engine will be sized to complete all maneuvers dry. Ostensibly, this is roughly the same corrected inlet flow rate as the 8,000 lb thrust engine, and this synergism will assist the designer in selecting a core size which would be suitable for both applications.

Conclusions

The probabilistic thrust sizing methodology proposed herein provides an analytical means of analyzing and tracking mission uncertainty during the early stages of design. This paper reviewed several tools used for uncertainty analysis and pointed out that the RSMonte and FPI methods are likely to be the most useful for probabilistic thrust sizing applications. Additionally, several guidelines were suggested for selection of uncertainty distributions as well as the application of probabilistic methods to the engine sizing process. These techniques were applied to the thrust sizing of a UCAV engine to show that, for the UCAV configuration considered herein, the engine yielding the highest probability of success is a low-bypass mixed-flow turbofan engine producing 8,000 lbs of thrust (afterburning). If one assumes that new mini-munitions are to be used as the primary UCAV weapon, then the best thrust is approximately 6,500 lb for the selected cycle, which equates to a core flow rate of 47.3 lb/s, roughly corresponding to a 50% scale F404 core (neglecting differences in turbine inlet temperature and compressor pressure ratio), and is a good starting point for sizing UCAV-related Joint Technology Advanced Gas Generator (JTAGG) and JTEC engine demonstrators.

Finally, this paper has shown that the closest existing engine has less than a 35% probability of meeting the thrust requirement. Based on this analysis, it is clear that the only viable options are to design a derivative engine using an existing core, or create a completely new design.

Although the authors are not suggesting that this technique is a panacea to all problems a designer faces, they are suggesting that it is a useful tool which can be used to assist the designer in making decisions in the face of uncertainty. It provides an analytical framework upon which to base design decisions and is also a useful tool in assuaging management skepticism and reluctance to spend money in the presence of risk.

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