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Identification of the Requirements Space Topology for a Rapid Response Strike System

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ABSTRACT

A method to identify the topology of an aerospace system's requirements space, specifically the location and type of the discontinuities that occur at the boundaries of the available technology and the physics of the system, allows the designer to make decisions as to the desirability of a specific solution state. Additionally, since a given set of requirements may produce multiple solutions the designer can compare his/her solution to other potential solutions. This allows an assessment of the requirements risk associated with a specific design. This paper addresses the need to visualize and understand the topology of the requirements space for a Rapid Response Strike System.

INTRODUCTION

The concept of a changing requirements space is not new to the aerospace industry. However, a rigorous method for address and evaluating the effect that stochastically uncertain requirements has on the selection of a system and the risks involved has not been developed. Investigation of the requirements space topology, specifically the boundaries of the feasible space for a given system is the first step in addressing this need. Knowledge of the topology also gives insight into other potential and competing solutions. This allows a design organization to develop knowledge of potential competing systems, and the ability to counter these systems accordingly.

BACKGROUND AND MOTIVATION

Typically the starting point complex systems design has been the identification of the perceived need. Proceeding from this identification it is then possible to create a set of requirements to address this need. The formulation of these requirements is the single most important act in the synthesis of the solution system. If the requirements are not properly formulated it will not be possible to design a system which satisfies the need efficiently if at all. At the same time, a given choice of requirements will eliminate the vast majority of the almost infinite complex systems that exist making it possible for systems designers to create a solution.

In the past the act of translating requirements into system design variables has been the task of expert designers. These designers have used years of experience and practice to hone their decision-making ability. While this system works well in practice it has it inherent limitations. First, since years of practical experience are necessary the retirement of experienced engineers entails the loss of knowledge within the organization. Second, constantly evolving needs and requirements dictate the ability to understand the risks involved with s specific design solution. For these reasons it is helpful to have an enumerated means of evaluating the effect of changing and uncertain requirements on potential vehicle designs. This paper provides a first step towards achieving this goal.

BASIC CONCEPTS

DEFINING VARIABLES

Every complex system, including aerospace systems, can be defined by a set of control and state variables. The state variables named so because they describe the specific state that the system resides in, typically number in the hundreds or thousands **[1]**. Further, for a given combination of state variables there is typically a unique response, i.e. the design of the Boeing 777 is completely specified by it state variables including:

- Wing Span
- Aspect Ratio
- Fuselage Length
- Fuselage Diameter
- Landing Gear Type
- Number of Engines

- Type of Propulsion System
- Cargo Capacity
- Passenger Capacity
- Manufacturer
- Etc.

The state variables; however, are not always independently set by the designer, instead they may be dependent upon a higher, less directly involved set of independent control variables. The control variables, which are usually much fewer in number, do not directly specify the final system; they do, however, specify a specific set of conditions in the state variables **[1]**. The response to a specific combination of control variables does not have to be unique and in many cases is not unique. Take for instance the YF-16 and YF-17. A specific set of military requirements, control variables, produced these two competing aircraft. While they may have been designed to the same control variables the specific combination of state variables was different, producing different aircraft designs.

In the world of vehicle design the system requirements can be viewed as the control variables. However, some requirements are not only control variables, but also state variables, i.e. a requirement for a solid rocket ballistic missile, defines the state of the propulsion system in addition to controlling other aspects of the design. The specification of a solid rocket system does not specify the type of solid rocket fuel and oxidizer that are to be used; this specific state maybe dependent upon other control variables and/or some sort of self imposed desirability.

Further, since the design of a complex system is really the creation of a system of systems it is possible to view the control variables for one level of system as the responses of a higher level and visa versa. An example of this is in the design of a propulsion system for a commercial aircraft. The specific requirements imposed upon the aircraft system produce a specific state response, i.e. the necessary amount of trust and thrust specific fuel consumption. While these are state responses for the aircraft they can be viewed as the requirements controls for the propulsion system.

Potential Vehicle Level Requirements Control Variables

The specific requirements for a vehicle system depend largely on the need that the system is to address. Therefore, a military system will have a different set of control variables when compared to a civil system. However, there are a set of universal classes of requirements, some of these are listed below.

- Range:
  - Range to Target
  - Combat Radius
  - Design Block Range
  - Economic Range
- Payload:
  - Warhead Delivered
  - Passengers Carried
  - Cargo Carried
- Time:
  - Block Time
  - Time to Target
- Size:
  - Weight Limitations
  - Geometry Limitations
- Noise:
  - T.O Noise
  - Landing Noise
  - Overpressure (Sonic Boom) Limits
- Flight Profile
- Survivability
- Fuel Type
- Ground Handling
- Cost:
  - LCC
  - Acquisition
  - O & S
  - RDT&E
  - Disposal

While this list is non-exhaustive it does give a feel for some of the primary control variables in vehicle system design. The common classes are typically found on all aerospace vehicles, be they airplanes, missiles, or launch vehicles. Similarly, a set of requirements control variables can be drawn up for the vehicle propulsion subsystem.

Potential Propulsion System Control Variables

The propulsion system is also defined by a set of “independent” control variables. However in this context the system is really a subsystem of the vehicle system; therefore, the “independent” control variables are really dependent upon the state of the vehicle. They are not however, dependent upon any other variables at the propulsion system level, and therefore they can be treated as independent variables. A non-exhaustive list of potential propulsion system variables is presented below:

- I_{SP} / SFC:
  - Dry
  - Wet
- Thrust:
  - Dry
  - Wet
- Speed:
  - Mach Limit
  - Dynamic Pressure Limit
- Size / Location:
  - Geometry:
  - Length
  - Diameter
  - Height

- Fineness
- Placement
- Weight

- Type:
  - Rocket:
    - Solid
    - Liquid
    - Hybrid
    - Electric
  - Turbine
  - Ramjet
  - SCRamjet
- Emissions:
  - Noise
  - CO_2
  - CO
  - NO_X
  - Smoke

An interesting feature of the propulsion system control variables is that they are determined by multiple higher levels, i.e. the ISP is a response from the vehicle system level, but an Emissions requirement could be a dictated requirement for the vehicle which is translated directly to the propulsion system level. A flow chart of the hierarchical model is shown in Figure 1. The inherent utility in using this hierarchical model is that it can be applied to any layer of a complex system or a system of systems.

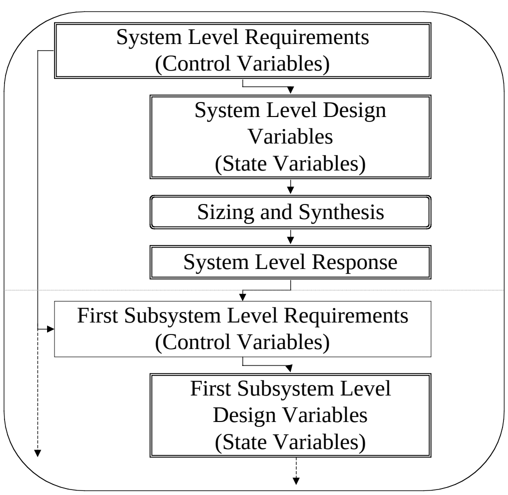

Figure 1: Proposed Requirements Hierarchy

RESULTING RESPONSE SPACES

General Comments

The topology of the requirements space is of great interest to the modern aerospace vehicle designer. As was stated above for a given set of control variables there is not necessarily a unique solution in the final space. This is true because multiple sets of state variables may exist which correspond to those state variables. It is, therefore, of value to investigate the resulting response space. Multiple benefits can be derived from knowledge of the control variable space. In the case of modern aerospace vehicle design, this control variable space corresponds to the requirements space.

In the past, the requirements issued in response to a need were very specific; i.e. they limited the number of solutions to only a few if not one unique system. In the typical case a strike fighter, strategic bomber, cargo aircraft, ballistic missile, et cetera was requested. Responses to the requirements were developed and if it was not practical to create a system to satisfy the entirety of the requirements some would be relaxed. This method has been employed with success throughout the last half century. However, with the new drive towards affordability, profitability, reduced cycle time, and program risk management, there is significant room for improvement. To address this need a more flexible means of specifying requirements is beginning to be used. In the new case the “need” and a few master requirements are set forth. The system designer then has to create a system that satisfies these requirements. However, there is now a significant possibility that there are multiple solutions for a given set of requirements, including multiple system types. This means that the system designer is left not only to decide the most desirable state variable that describe a strike fighter, but also to determine, for a given set of requirements, that the strike fighter and not a cruise missile is the most desirable choice.

Further, because of the rapidly shifting nature of politics, economics, and technology; it is highly likely that the need that the system will be called to address will change over bother the operational life of the system and the development period. These changes will affect the ability of the system to perform its mission. Historically, as the needs have evolved modifications were performed on existing systems to achieve some measure of capability. If this new capability was insufficient to meet the new need a new system or derivative version of the system was developed. A primary example of this evolution is the path taken by the F-18 from the C/D to the E/F variant. This evolution in requirements and system technologies was illustrated by DeLaurentis and Mavris **[2]**. More drastic changes in the requirements may cause changes in the vehicle design that diverge from the previous solution.

The divergent points in the requirements space is of greater interest to program managers and program risk assessors. Common sense dictates that there are places where the resulting state response behaves discontinuously to small changes in the control variables. These singularities are of the greatest interest; it is here that a specific combination of subsystems reaches the limits imposed by either technology or physics.

Types of Frontiers

Technology Frontiers

A technology frontier is one in which the technologies used in a system or subsystem are unable to provide higher performance. Example technology frontiers are turbine inlet temperature, maximum skin temperature, and available computing power. Each one of these frontiers has been pushed forward over the years. Therefore, the identification of new technologies has the potential to change the location of the frontier over time.

Physical Frontiers

The other type of frontier is one that is imposed by physics. The term physics is used somewhat loosely in this discussion, implying the theoretical limits of a subsystem due to the behavior of such things as the thermodynamics of the working fluid, in addition to such physical limits as the necessity to exceed the speed of light. An example of the former is the theoretical I_{SP} limit for a hydrocarbon ramjet based upon the inability of the working fluid to recombine and return the chemical energy to the flow. An example of the later would be the response time limit for a laser system; it would not be possible to hit a target on the moon from earth with a response time of only one-second.

Requirements Space Topology

Technology and physical limits create three primary types of discontinuities that can occur in the control space. The first two are examples where a simple functional relationship or set of relationships between the control variables can be determined. This means that there are different a unique solutions on either side of the discontinuity. The simplest of these is the step discontinuity. Here the is a sudden change in the resulting system type for a infinitesimal change in the control variables, e.g. going from a strike fighter to a missile as the response time decreases. If the control variables are returned to their original settings the reverse jump will occur at the same location. This type of jump is illustrated, for a set of linear responses in a two-dimensional control space, in Figure 2.

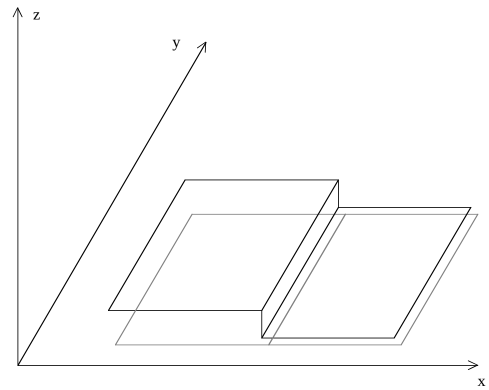

Figure 2: Typical Functional Discontinuity

The second type of discontinuity is one in which there is a space where no solutions exist as the control variables are changed. Again if the control variables are returned to their original values the discontinuity will occur at the same location. It is therefore, possible to describe this type of discontinuity as a conditional set of simple functions in the control space. A simple example of this type of discontinuity is illustrated in Figure 3.

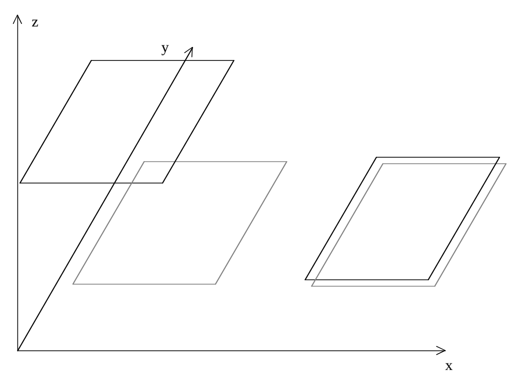

Figure 3: Typical Functional Discontinuity, with a no Solution Space

The third type of commonly observed discontinuity is one that possesses hysteresis. In this case for certain values of the control variables there is more than one solution. Further, because of this hysteresis the discontinuity will not occur at the same values of the control variables. A simple case of a hysteresis discontinuity is shown in Figure 4.

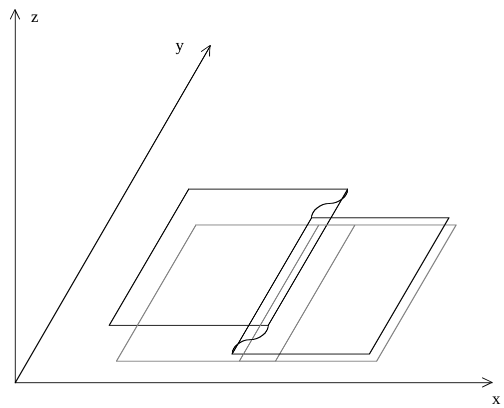

Figure 4: Typical Discontinuity with Hysteresis

While all of the discontinuities are of use, the presence and location of those that display hysteresis are of the greatest interest. It is in the space where more than one state solution exists, that the system designer must be able to decide as to which solution is the most desirable.

Discontinuities displaying hysteresis are extremely common in nature, one of the easiest to relate to is the change of gait between walking and running for a human. As the speed of travel is increased, from a standstill, a man will progressively walk faster, until at a certain speed, determined by a number of biological factors, he switches to an entirely different gait, that of running. If he continues to increase speed he will continue with a running gait until he is unable to run any faster. While the discontinuity in its own right is unremarkable it is the fact that when the man slows down he will continue running even after he slows down past the speed at which he switched from a walking gait to a running gait **[3]**.

In the case of the human gait, the human starts in the gait that requires the minimum energy expenditure. As the speed increases this minimum goes from being unique to a global minimum. It is therefore logical that the man would continue walking. As speed increases further the minimum changes from a global minimum to a local minimum, and eventually disappears. Depending upon the type of system, it will either change discontinuously when the minimum is no longer global or when it disappears entirely. The former illustrates a system without hysteresis and the later one that possesses hysteresis **[1]**. Another way of looking the discontinuous changes is by looking directly at the appearance and disappearance of the minima. This is illustrated in Figure 5, Figure 6, Figure 7, and Figure 8.

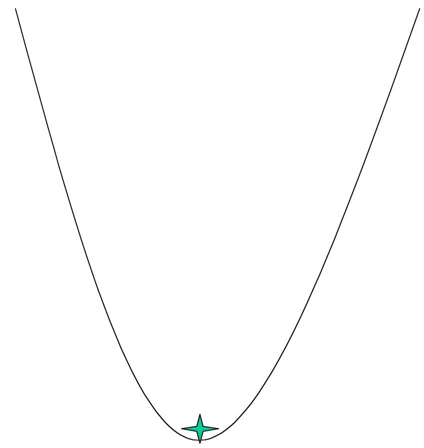

Figure 5: Initial Control Variable Settings, Single Minimum [4]

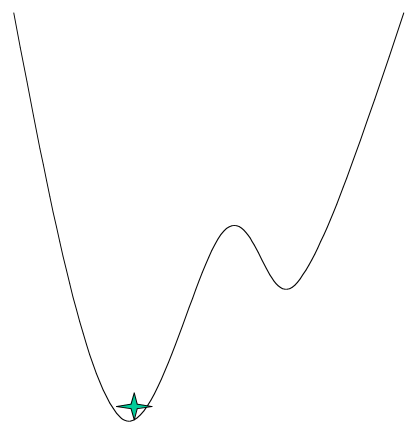

Figure 6: Second Control Variable Settings, Initial Minimum is now a Global Minimum [4]

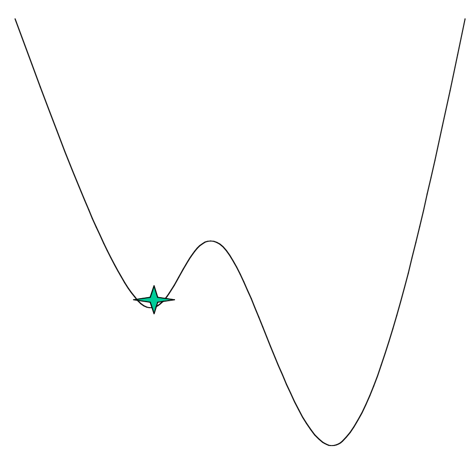

Figure 7: Third Control Variable Settings, Initial Minimum is now a Local Minimum [4]

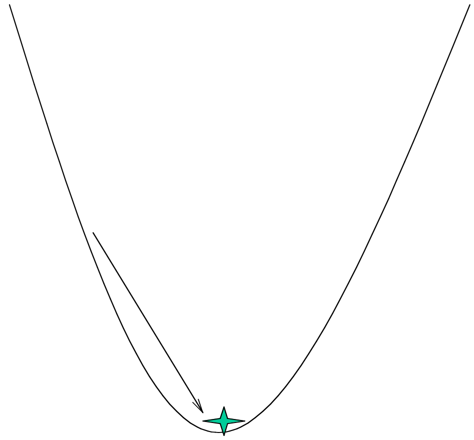

Figure 8: Fourth Control Variable Setting, Original Minimum has Disappeared, Discontinuous Change to next Minimum [4]

Additionally the type of discontinuous change that occurs may differ depending on the settings of other control variables. This is illustrated in Figure 9.

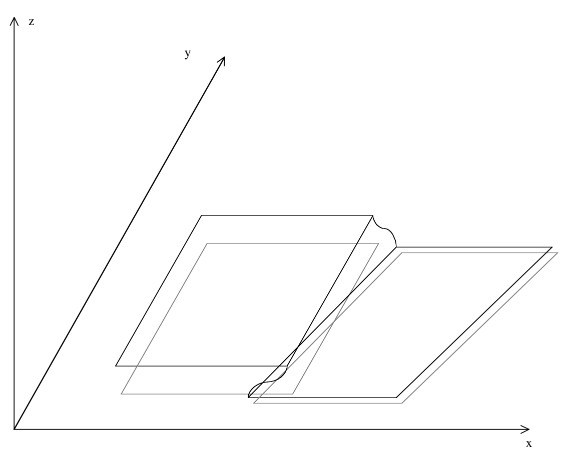

Figure 9: Example of a Disappearing Hysteresis [1]

SYSTEM STUDIED AND METHOD USED

SYSTEM DESCRIPTION

To explore the topology of a requirements space such as that described in the previous section, a relatively simple example was undertaken. The system being explored is one that fulfills the need for a "Rapid Response Strike System." (RRSS) This system was based upon the need laid out for the Hypersonic Strike Fighter (HSF) that the authors have previously studied **[5]**. In the previous paper the authors investigated the proper selection of specific system requirements to achieve the most desirable system. In that case the uncertainty of the requirements was taken into account, but no alternative systems other than variations on the HSF technology set were explored. In the current instance two primary systems were investigated to determine the requirements space topology: an unmanned strike aircraft, and a high speed cruise missile.

Strike Fighter System

The strike fighter weapons system studied was based upon the one used by the authors in the previous paper **[5]**. No major changes were made to the system design or composition. The system is a two-cycle turbine boosted ramjet cruise vehicle, with a delta wing planform, and a nose inlet.

Cruise Missile System

The cruise missile was based upon notional system requirements for an air or surface launched high-speed missile systems. It is a rocket boosted, no-ejectable, ramjet powered system with a circular body and small wings.

Requirements Examined

To further limit the scope of this paper to a manageable size, it was necessary to minimize the number of potential control variables or requirements that were investigated. The specific requirements that were investigated are listen in Table I.

Table I: Requirements Evaluated in Current Study

Requirement	Lower Bound	Upper Bound
Time-to-Target	15 min	60 min
Mission Radius	750 nm	3,000 nm
Payload Weight	750 lbs.	9,000 lbs.
Gross Weight	1,500 lbs.	100,000 lbs.

The four primary requirements each represent a category from the list given in the previous section

- Time – Time-to-Target
- Range – Mission Radius
- Payload – Payload / Warhead Weight
- Size – Gross Weight

Additionally, due to the nature of the space and the limitations inherent in the Excel solver routine the wing loading was also specified.

SPACE EVALUATION METHOD

The control variable space was evaluated using a multilevel grid method, on a model created in Microsoft Excel **[6]**, using standard energy based equations. The requirements were specified and obtained using the

Solver add in module. The model used was a modified version of that used previously by the authors **[5]**. The results of the grid were then graphed using both Excel and JMP from the SAS institute **[7]**.

To provide the necessary resolution 1,536 run factorial grid was used for both the strike fighter and the missile. In the case of the Mission Radius and Time-to-Target the values were identical for both systems. However, it would be impractical to use the same payload and gross weight limits for both the fighter and the missile. Technological and physical limit contours were then evaluated for similar cases for each system with respect to the time to target and the mission radius. The primary responses being tracked were the Require Specific Impulse (I_{SP}), Cruise Mach Number, and the Required Boost Thrust to Weight Ratio (T/W).

RESULTS

The results obtained were analyzed to determine the technological and physical frontiers for the primary responses.

REQUIRED SPECIFIC IMPULSE

The I_{SP} required to achieve the stated mission varied widely depending on the specific set of requirements chosen. Because of the shear amount of data, only the most interesting portion of the requirements space is shown here. Figure 10 illustrates the required I_{SP} for a fixed wing, recoverable, unmanned strike fighter with a 2,250 lbs. payload, a 50,000 lbs. gross weight, and an 80 psf. W/S.

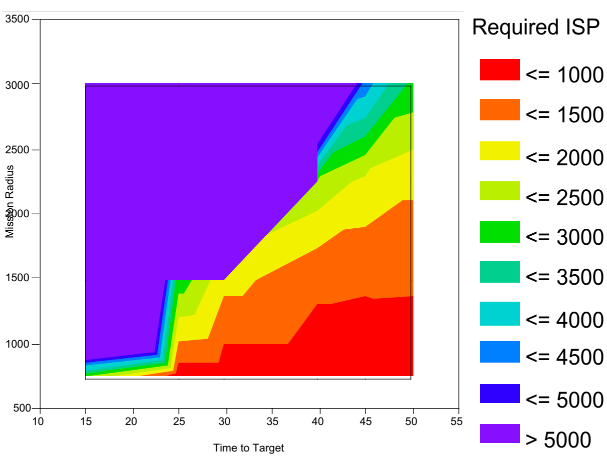

Figure 10: Required I_{SP} Contours for a Strike Fighter

The required I_{SP} increases significantly as the mission radius increases and the time-to-target decreases. If a limit on the vehicle size is placed at 50,000 lbs., the system is one of relatively short range and slow response time.

Conversely, a 3000 lbs. surface launched cruise missile with a relatively small, 750 lbs., warhead can perform significantly better, achieving similar range and a shorter time-to-target for the same required I_{SP}. This is illustrated in Figure 11.

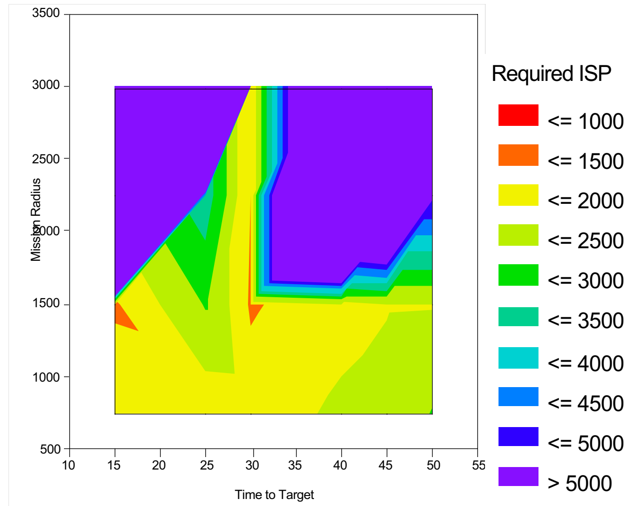

Figure 11: Required I_{SP} Contours for a Missile

Except for the short-range long response region the missiles required I_{SP} is lower than that for the strike fighter, A good comparison is to look at a technological limit of an 1800-second I_{SP} for a ramjet powered system. Figure 12 illustrates the regions of the time-to-target and mission radius space for which it is possible to use a system powered by a cruise engine that provides less than an 1800 second I_{SP}.

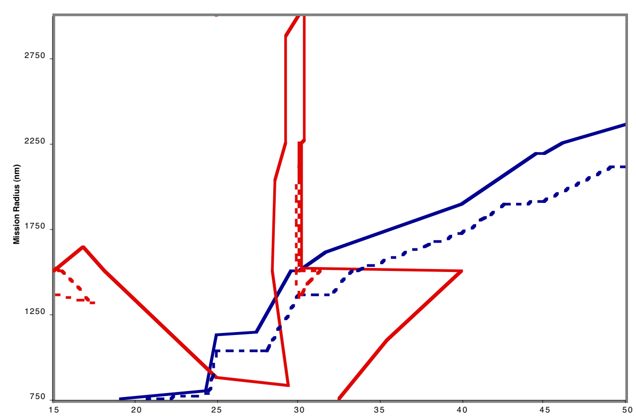

Figure 12: Aircraft (Blue) / Missile (Red) I_{SP} Contour Comparison

Note: The Dotted lines are the 1,500 second I_{SP} contours and are included to indicate the downslope side of the line

Of interest is the fact the while there is significant overlap in the feasible spaces, the missile requires an I_{SP} higher than 1800 second for the lower right hand region, indicating that response time is less important for satisfying the need, a reusable turbine powered aircraft is the system to be used. This makes intuitive sense. Conversely, if the need places a tight response time requirement then the only available solution is that of the missile, and it is limited to relatively short ranges.

REQUIRED THRUST TO WEIGHT RATIO

Similarly, the need to investigate the required boost Thrust to Weight ratio (T/W) is also important, again there is a direct technology limit that can be obtained with state of the art (SOA) technology. Because of the differing boost systems use in the fighter and missile systems the respective technology limits are not at the same T/W. Figure 13 shows the requirements contour space for the strike fighter.

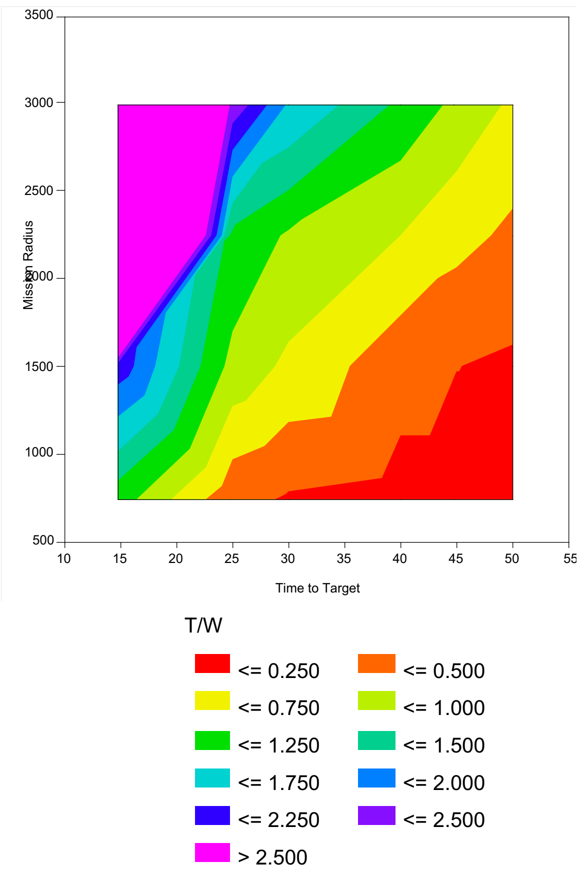

Figure 13: Required T/W Contours for an Aircraft System

As with the required I_{SP} the required T/W increases significantly for increasing mission radii and decreasing time-to-target requirements. Figure 14 shows the same chart for the missile system.

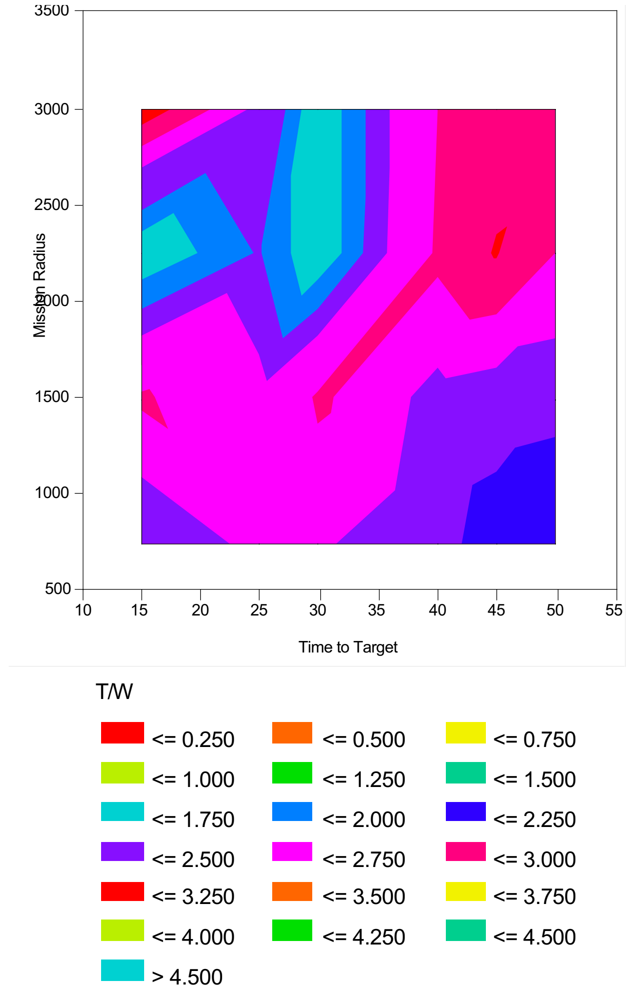

Figure 14: Required T/W Contours for Missile System

While the aggregate T/W required for the missile is higher than that for the aircraft, the inherent T/W of a solid rocket is higher than that for a turbine engine. Further, the lack of the necessity to reuse the vehicle means that a higher vehicle T/W is achievable. Therefore, a technology limit needs to be placed upon both the aircraft and the missile to allow a comparison of each system's feasible space. The current SOA of turbine engine technology places the maximum practical vehicle T/W of approximately 1.25 for a reusable aircraft. Conversely, it is possible to achieve a system T/W approaching 3.0 for a solid rocket boosted missile. Figure 15 displays the limit contours for both systems with respect to time-to-target and mission radius.

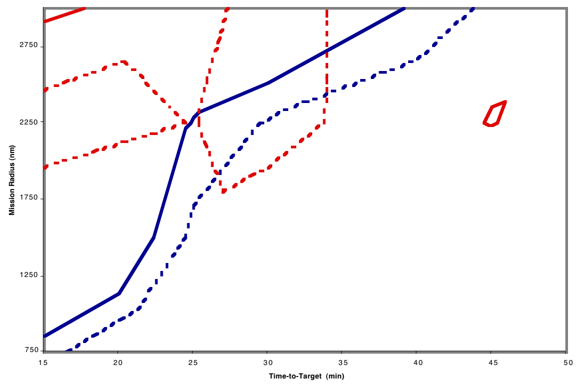

Figure 15: Aircraft (Blue) / Missile (Red) T/W Contour Comparison

Note: The dash lines indicate the downslope side of the limit contours.

The interesting thing to note is that while the aircraft has a definite technology limit with respect to accessing the upper left corner of the requirements space, the same cannot be said for the missile. In the case of the missile there is effectively no technology limit with respect to the required T/W.

REQUIRE CRUISE MACH NUMBER

The third portion of the response topology to be investigated is that of the required cruise Mach number. Since both vehicles are of the airbreathing, lifting type the Mach number comparison can be made directly. Figure 16 shows the required Mach number contours for the aircraft system. Figure 17 shows the same contours for the missile system.

Again, the missile's feasible space extends to lower time-to-target requirements and greater mission radii. A direct comparison of the limit contours, in this case Mach 6 for a simple hydrocarbon fuel ramjet, is given in Figure 18.

The combination of all of the responses and their respective technological and physical limits produces the space in a system is able to meet the need is was designed to address. The topology of this space and specifically the discontinuities present in it are of the greatest interest when determining the type of system that should be used, and the risk involved with that specific choice of system.

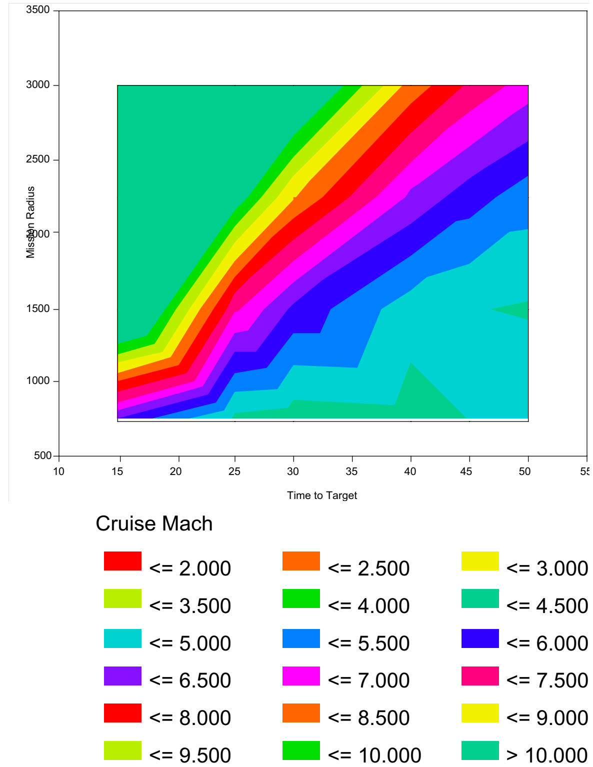

Figure 16: Required Cruise Mach Number Contours for an Aircraft System

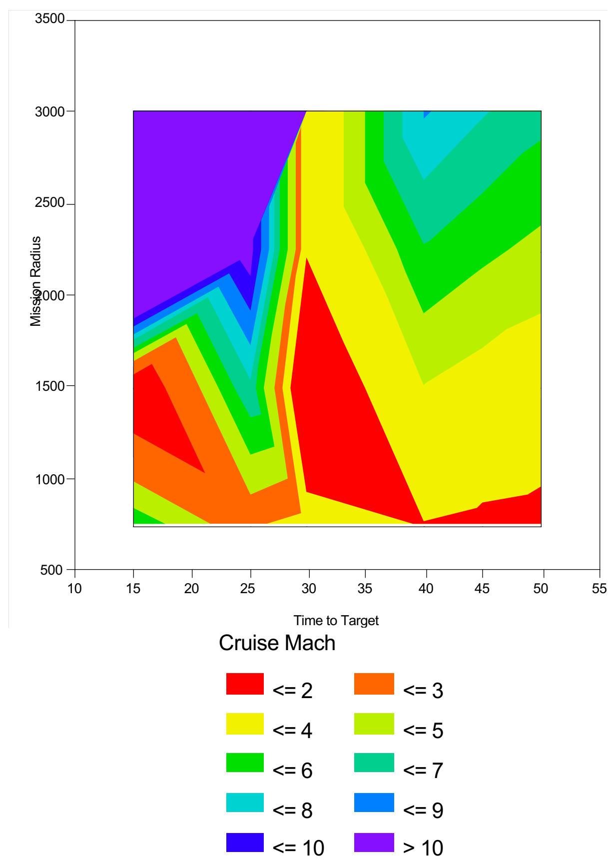

Figure 17: Required Cruise Mach Number Contours for a Missile System

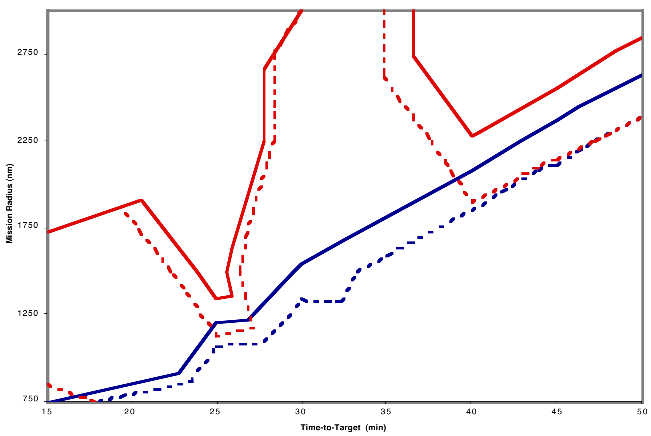

Figure 18: Aircraft (Blue) / Missile (Red) Cruise Mach Number Contour Comparison

FUTURE WORK

As the number of control variables increases two primary things happen. First the space develops multiple minimums for each unique set of control variables, i.e. there may be more than one T/W, I_{SP}, and Cruise Mach combination which satisfies the requirements for a given system. These multiple minimums may be inside or outside of the technological limits. Additionally, they pose problems for standard optimizers, which were used in this paper to converge on the control variable settings. Second, the size of the grid that is needed to fully explore the nature of the topology of the space increases considerably, making it combinatorically infeasible to explore the entire space. Therefore, it since only the discontinuities are of significant interest it makes sense to use a method such as a genetic algorithm to find the discontinuities and the local minimums in the solution; future work will focus on this aspect in addition to fast ways of describing the discontinuities mathematically.

Furthermore, a rigorous method for addressing the effects of the stochastically uncertain nature of the requirements must be developed to provide a useful tool for assessing the risk and desirability of a given system selection. Additionally, techniques and methods for effective visualization of the resulting topology must be developed and advanced. Otherwise, it will not be possible to quickly and satisfactorily share the knowledge gained amongst the necessary decision-makers.

CONCLUSION

The ability to view and understand the topology of the requirements space for a complex system is critical. This paper has attempted to set forth a basic means to understand the space, and provide an example of this for a RRSS; both an uninhabited fighter and a cruise missile system were investigated. The resulting topology, specifically the technological and physical boundaries presented by the system were discovered and compared. Without any further determination of desirability it is impossible to definitively determine the "better" system. However, general statements about the regions of the requirements space that each system is most capable were made, i.e. that the cruise missile is better for the shorted range quicker response missions where reusability is not a great concern, and the strike fighter is a better choice for the longer range, slower response, higher flexibility missions. Further work must be performed; however, to develop a truly usable system for evaluating the choice of a specific system, its desirability, and the risks involved.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Control Variable: Independent variable that controls the response of the system. A unique combination does not necessarily produce a unique response

HSF: Hypersonic Strike Fighter

I_{SP}: Specific Impulse

M: Mach Number

RRSS: Rapid Response Strike System

State Variable: Variable that determines the state of the system, or actual response. May be dependent upon the control variables. A set of state variables defines a unique response.

T/W: Thrust to Weight Ratio