DISSERTATION

AIRCRAFT SURVIVABILITY MODELING, EVALUATION, AND OPTIMIZATION FOR MULTI-UAV OPERATIONAL SCENARIOS

Submitted by

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ABSTRACT

AIRCRAFT SURVIVABILITY MODELING, EVALUATION, AND OPTIMIZATION FOR MULTI-UAV OPERATIONAL SCENARIOS

The unmanned aerial vehicle (UAV) has become a prominent aircraft design throughout aerospace applications including commercial, civilian, and military. A UAV is preferred in some missions and applications due to its unique abilities compared to manned aircraft. This dissertation aims to define an improved understanding of the concepts and modeling of aircraft survivability, as applied to UAVs. Traditionally, survivability as a field has defined and considered survivability primarily in the context of manned aircraft, and single aircraft. With UAV's increasing importance in multi-UAV operational scenarios, it has become increasingly important to understand aircraft survivability for singles and groups of UAVs.

This research effort has been structured into three research questions defining contributions in survivability modeling, validation, and UAV aircraft design. Research Question 1 seeks to demonstrate the feasibility of a parametric model of UAV survivability. The result is a UAV survivability model and simulation which illustrates key tradeoffs within UAV survivability. The effects on survivability on UAV design characteristics (speed, wing area, drag and lift coefficients) is quantified specific to the detailed lethal envelope simulation method. Research Question 2 aims to verify and validate the UAV survivability simulation, providing evidence of the predictive capability of the survivability simulation results. Evidence is presented for verification and validation through comparison to previous modeling efforts, through solicitation of expert opinion, and through parameter variability and sensitivity analysis.

Lastly, Research Question 3 seeks to apply the simulation results to multi-UAV tactical evaluation and single aircraft design. The results illustrate the level of improvement that can be realized through UAV design including armoring (a 25% survivability improvement through 1000kg of armoring), speed increases (a 100 mph increase in cruise speed realizes a 14% decrease in killability), and other relevant design variables. Results also demonstrate that multi-UAV tactics can improve the survivability of UAVs in combat. Loyal wingman tactics are simulated to increase the survivability of a C-130J (equivalent UAV) from 19.8% to 40.0%. Other single UAV tactics such as fuel dumping, afterburners are evaluated under the same framework for their relative effectiveness.

This dissertation answers the described research questions by presenting an aircraft survivability evaluation approach that relates survivability with modern UAV applications, emerging threats, multi-UAV tactics, and UAV design. Aircraft survivability encounters with modern UAV countermeasures are considered and simulated. UAV metrics of performance are modeled and simulated to describe aircraft design parameters sensitive to improving aircraft survivability. By evaluating aircraft survivability with a modern multi-UAV tactical perspective, this study seeks to provide the UAV designer with more complete vision of survivability-derived design criteria.

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1. INTRODUCTION

The focus of this dissertation is the modeling, design, and operation of unmanned aerial vehicles (UAVs) with an emphasis on evaluation and optimization towards metrics of aircraft survivability. This chapter presents an introduction and motivational background to the topics of modeling and simulation, aircraft survivability, and aerospace engineering. Modeling and simulation is widely used in the aerospace community for design decision support regarding tradeoffs among performance, cost, and aircraft survivability. A focus of design for this dissertation is the concept of aircraft survivability. Aircraft survivability describes the capability of an aircraft to survive an encounter with an enemy, and aircraft survivability is understood to be an important metric for combat mission analysis. By understanding an aircraft's survivability, decision making for war game scenarios can be supported by engineering modeling and simulation. Given the importance for aircraft survivability, the aerospace industry strives to design and manufacture aircraft with high survivability to provide to their customers. The motivation of this work is to develop the concepts and considerations of aircraft survivability for UAVs, and to enable an aircraft survivability-inclusive approach to UAV modeling and simulation. Research questions seek to provide evidence that modeling and simulation can improve UAV aircraft survivability to provide more high value aircraft designs for practical combat scenario applications.

2. BACKGROUND

Modeling and Simulation

A model is an abstract representation of behavior, structure, or information, and can be virtual or physical. Models typically have inputs and outputs, and have utility in describing physical phenomenon [Borky] [Ziegler]. A simulation is a representation of a model within a time-based sequence, often represented by states [Loper] [Ziegler]. Within the context of aircraft design, having the ability to abstractly represent an aircraft-specific phenomena though modeling and simulation can provide insight into the realistic capabilities of the aircraft. This dissertation uses modeling and simulation to better understand aircraft survivability under novel perspectives and modern applications.

In order to have utility for decision-making, a model must undergo a process of verification and validation to understand whether a model is fit for purpose. Verification is the activity of reasonably arguing a model's proper implementation with respect to the model description and solution [Moffat] [Stolfi]. Typically, verification references established theories and seeks to compare measurements of the model to established theories while describing explanations [Oberkampf]. For instance, a model of turbulent flow could be verified through comparison to established theories suggesting that phenomena [Selig] [Somers]. Validation is the activity of deterministically arguing the amount of accuracy in a model representing the physical world under the intended uses [Moffat] [Stolfi]. Validation often uses measured information from the model to provide an argument for agreement between experimental evidence and modeling and simulation metrics [Sargent]. An example of a validation comparison would be comparing the point of turbulent flow separation from simulation, and from a representative airfoil in a wind tunnel experiment [Berg] [Selig] [Somers]. Metrics of validation can include modeling uncertainty, pure error estimate, and experimental error [Kline] [Moffitt]. Validation often relies on verification for support [Sobieszczanski-Sobieski]. These metrics and physical comparables are typically accepted as evidence of verification and validation in the modeling and simulation community. The modeling approach adopted in this work uses common verification and validation methods to demonstrate predictive power, and to convince the modeling and simulation community our findings.

Aircraft Survivability

The term "aircraft combat survivability" (ACS, or AS) is defined in *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition* as "the capability of an aircraft to avoid or withstand a man-made hostile environment" [Ball]. Aircraft combat survivability is one of the most important metrics of aircraft performance and design [Hall]. Survivability is the ability of an aircraft to avoid or endure an artificially hostile environment and has a relationship with killability, susceptibility, and vulnerability [Ball]. Where killability is an aircraft's inability to avoid or endure an artificially hostile environment and is comprised of the product of susceptibility and vulnerability [Ball]. Also, susceptibility is the aircraft's inability to avoid hostile attacks [Ball]. Lastly, vulnerability is the aircraft's inability to withstand hostile attacks [Ball]. An understanding of aircraft survivability has been demonstrated to have considerable impact on military tactics and strategic decision making in combat [Helldin].

The purpose of survivability modeling is to provide decision-makers with relevant, credible evidence, conveyed with some degree of certainty or inferential weight, about the survivability of an aircraft [Ball]. To model an aircraft's survivability for purposes of design, numerous methods have been developed that can be incorporated into design, refinement, maintenance, and operations stages of the aircraft lifecycle [Vincent]. Some important modeling methods include the methods of Ball and shot-line geometrics for precision shots on subsystems, shown in Figure 1, and consider armored air vehicles [Ball] [Li] [Yang]. Many of the design tools that are available today implement Ball-type and shot-line methods, including BRAWLER, AFSIM, etc. [Hall] [Noh]. All the tools surveyed in this section are highly proprietary and typically require specific reasoning and/or clearance to acquire.

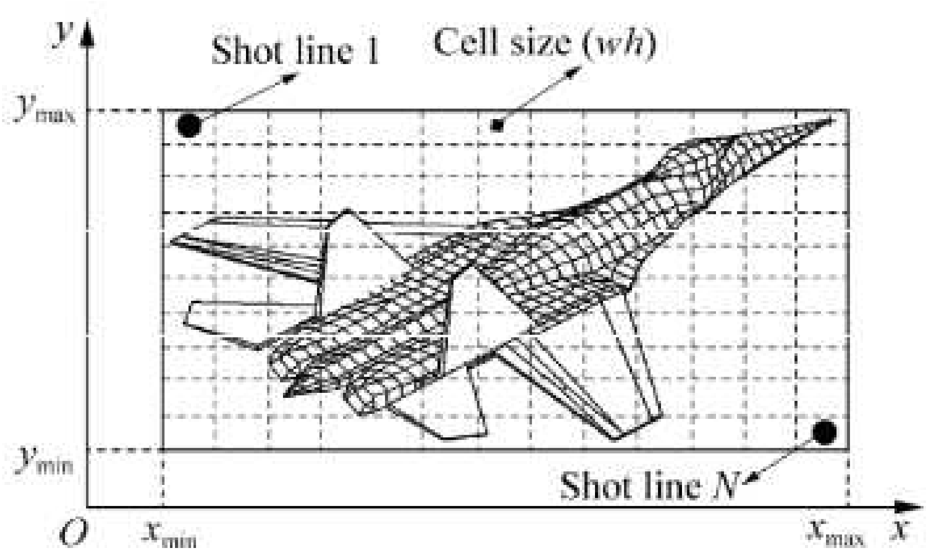

Figure 1. Traditional Shot-line Geometric Approach [Yang]

For the shot-line geometrics approach, attacks' effectiveness on the air vehicle is evaluated by the accumulation of attacks' effects on the aircraft subsystems. A shot-line is measured to the subsystems within the shot-line path and the attacks' effects are relative to subsystem armoring, subsystem redundancies, attack effectiveness, and various other parameters [Yang]. Measuring shot-line geometrics is effective for aircraft design scenarios, yet somewhat unpredictable in a mission level engagement. For our project, we recognize shot-line geometrics as specific attacks at a subsystem level to system level. In result, shot-line geometrics become out of scope due to the focus of our survivability approach is system level to mission level. Instead of shot-line geometrics, this dissertation focuses on other higher-level and generic methods.

After thorough literary reviews, the current state of being aircraft survivability was discovered as lacking in UAV applications and modeling and simulation. As the literary research progressed, Ball's hits on aircraft method was commonly used and appropriate for almost every aircraft survivability application and analysis. Other evaluation methods such as shot-line geometrics were discovered as effective and useful, but too detailed for system level aircraft survivability analyses. With more review progression, other aircraft survivability tools were recognized including BRAWLER and AFSIM. As the tools were discovered, they were noted to be difficult to acquire due to institutional withholdings. Next, Wang's method was discovered as an effective opportunity to include the range and time threatened by an enemy entity. After that, understandings of emerging and modern threats were discovered in the form of digital pheromones, loyal wingman, and swarming [Humphreys] [Sauter]. These in whole have been the basis of the aircraft survivability improvement approach.

Relative to these traditional AS methods, new AS performance metrics and AS concepts have been developed to keep pace with emerging aircraft tactics and technologies [Couch]. For example, a traditional AS metric of performance is "hits on target", the number of munition hits that an aircraft can incur before failure [Ball]. New AS concepts understand that modern anti-aircraft munitions are far more effective than traditional munitions and that there may be ways to avoid being hit by enemy fire at all [Eaton] [Erlandsson] [Schaffer]. The modern threats today include MANPADS, AIMs, RIMs, etc. where the traditional threats have been flak, small arms, etc. [Clothier]. The newer modern methods discovered take into account more advanced ways to improve aircraft survivability.

The newer survivability methods are similar in concept, with specific differences in practice. Depicted in the next few figures is each survivability application in a universal depiction language. The white UAV near the right of the images represents an air vehicle to be analyzed. Near the center of the images an anti-air emplacement represents a hostile entity. Surrounding the hostile entity, an orange circle illustrates the detection range and a red circle shows the lethal envelope. Lastly, the blue dashed arrow line(s) across the image represents the air vehicle flight path. The figures aid the depiction of each modern aircraft survivability application.

Firstly, the lethal envelop developed by Wang considers an aircraft threatened only when within range of a hostile entity [Wang]. Figure 2, shows one single vehicle traversing a combat space. Within the combat space is a hostile entity centered. The air vehicle travels past and directly above the hostile entity. As the aircraft approaches and leaves the hostile entity, the aircraft enters and leaves the detection range and lethal envelope [Erlandsson] [Wang]. Within the detection range, the aircraft is able to be observed by the hostile entity. Within the lethal envelope, the aircraft is vulnerable to hostile entity attacks [Erlandsson] [Wang]. Scenarios similar to Figure 2 are simulated and iterated to observe the aircraft survivability. The lethal envelope approach represents a simplistic, bare-bones analysis for aircraft survivability. Today, methods have been developed to improve an aircraft's chances of surviving hostile entity encounters.

Modern methods to reduce aircraft killability as a whole have been considered. For example, the digital pheromone approach, described in Figure 3, seeks to sense and avoid hostile areas [Frye] [Sauter] [Teo]. The loyal wingman approach, shown in Figure 4, seeks to intercept enemy fire and reduce hits on the aircraft [Humphreys]. Swarm approaches, illustrated in Figure 5, consider aircraft survivability as a system rather than one vehicle [Wang]. Each of these methods is a step toward a more modern and relevant aircraft survivability analysis.

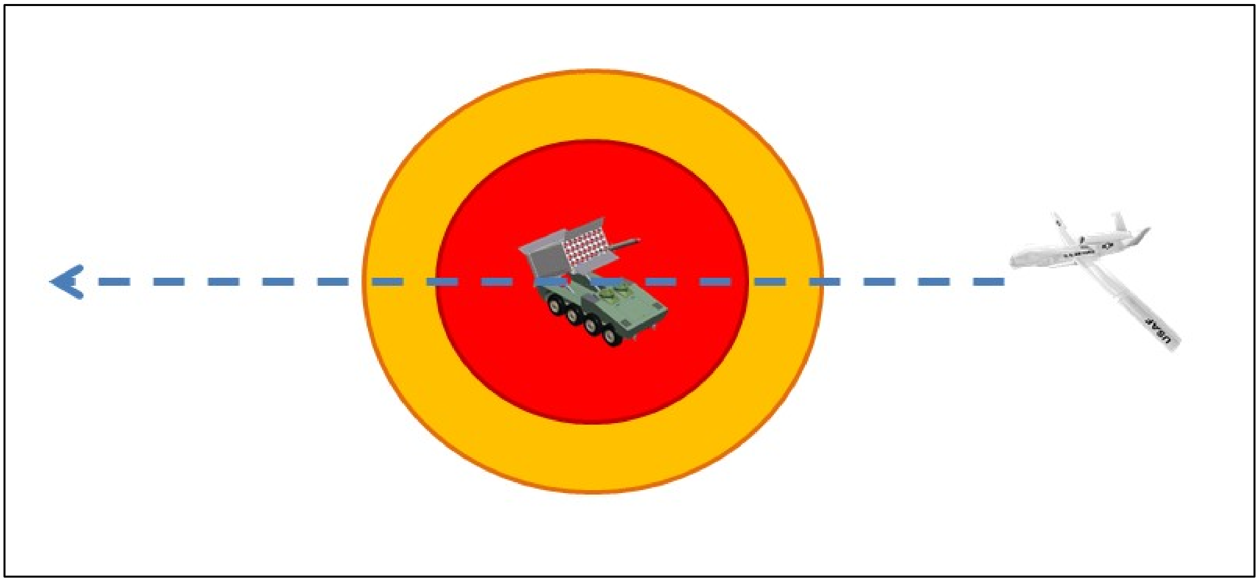

Figure 2. Simple Lethal Envelope Scenario [Wang]

Digital pheromones are identifiers of area allegiance and are typically communicated to system entities. In Figure 3, a digital pheromone scenario is depicted. Similar to the lethal envelope approach, there are familiar elements: lethal envelope, detection range, flight path, etc. [Helldin]. In the digital pheromone scenario, the green area is the area denoted as safe by the air vehicle. The red box near the center of the image is the hostile area denoted by the air vehicle. Distinguishing between the two safe and unsafe areas provides the air vehicle with the opportunity to avoid an unsafe encounter, increasing survivability [Eaton] [Erlandsson]. For aircraft survivability, digital pheromones plays the role of locating potential hostile areas and deciding how best to avoid [Jia]. Certain areas are assigned their hostility type: hostile, neutral, or safe and are communicated to the navigating aircraft. With the area being known, the vehicle can choose the navigation route minimizing exposure to enemy hits [Zhang]. By knowing and/or avoiding hostile areas, the aircraft is less likely to take enemy attacks, in result improving the aircraft survivability.

In AirSurF, digital pheromones are utilized to various scenarios to determine aircraft survivability when navigating the least exposure to hostiles. The framework assigns hostility to square areas throughout the scenario for the vehicle to discover and decide. The methodology has the vehicle finding the hostile area, checking the surroundings, and deciding how to progress. The vehicle will often avoid hostile areas unless there is no other navigation option [Zhou]. By avoiding enemy hostile areas, the vehicle can reduce the amount of hits it will receive, improving survivability.

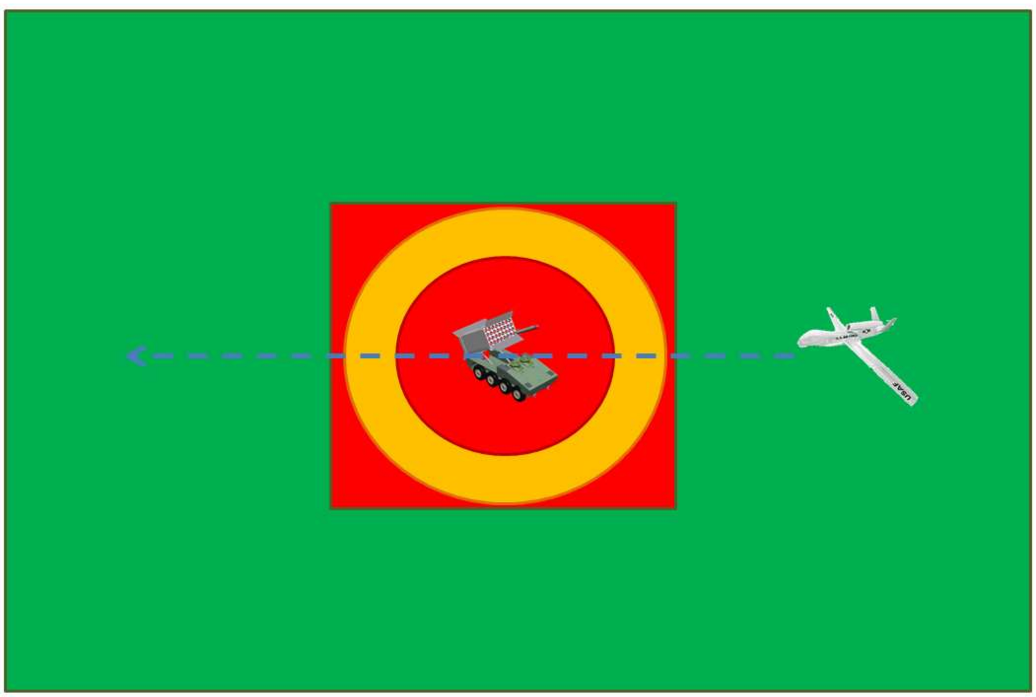

Figure 3. Digital Pheromone Approach [Sauter]

Loyal wingmen are dedicated air vehicles to protecting an escort vehicle either offensively and/or defensively [Humphreys]. Figure 4 shows a loyal wingman scenario where multiple vehicles are escorting an air vehicle. The air vehicles on each side of the centered air vehicle are loyal wingmen, intended to protect the centered air vehicle. Protecting the centered vehicle has many applications, defensively and offensively. Loyal wingmen are capable of intercepting hostile entity attacks as well as neutralizing hostile entity threats [Sonawane]. The loyal wingman is a newer concept in reference to unmanned aerial vehicles. Autonomous countermeasures with loyal wingman defending an escort vehicle are being explored. Possible solutions include intercepting incoming attacks and/or deploy countermeasures to enemy threats/entities [Humphreys]. Each consideration is investigated with our approaches of modeling and simulations.

Another capability of the loyal wingman is to have offensive measures. The loyal wingman is often able to attack the hostile enemy to eliminate any possible future attacks. The elimination of threats, in result, reduces the hits of the escort vehicle. Countermeasures can include munitions payloads, jamming, lasers, etc. Countermeasures can be an effective survivability preserving option to simulate with.

A current example of a loyal wingman is Boeing's development of a loyal wingman UAV for the Royal Australian Air Force. In their scope, four to six vehicles operate in conjunction to an escorted vehicle. The performance is similar to a fighter with sensor applications to conduct reconnaissance, surveillance, intelligence, and electronic warfare. Also, the intent is to provide information to the escorted vehicle for decision making as well as combat hostile entities defensively and offensively with electronic warfare. An instance of defensive electronic warfare combat could be disabling an incoming missile with jamming [Mahulikar]. Where, an instance of offensive electronic warfare could be disabling an anti-air ground installation with directed energy. Each capability could be invaluable for supporting an escort vehicle [Humphreys].

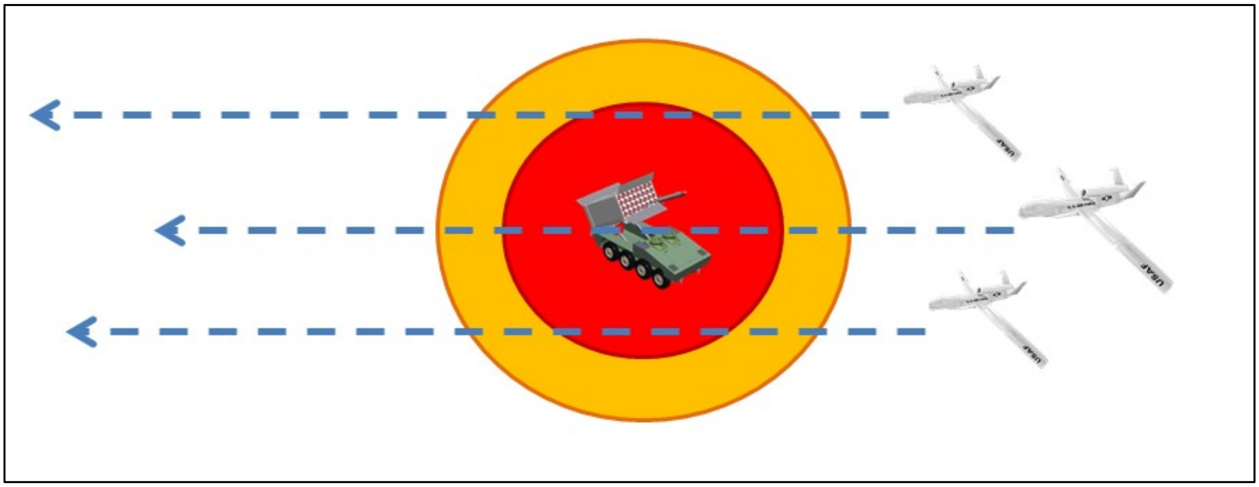

Figure 4. Loyal Wingman Approach [Sauter]

Swarms are systems in multi-vehicle configurations. Depicted in Figure 5, swarms can be seen as multiple vehicles encounter hostiles as a system. Often swarms have self-awareness with the vehicles in the system. The traditional approaches for swarming are a collection of vehicles working to a common objective cooperatively. Vehicles in swarms are often expendable to fulfill the decided upon objective. By implementing swarming, the system will have a higher chance for survivability due to multiple vehicles enduring attacks rather than one vehicle.

Swarm is a system level of vehicle composition. Traditionally, aircraft survivability is of a single vehicle. With the swarm, survivability is measured in reference to the entire system of systems. There are two means to a swarm approach. A one-hit fail system or a system comprised of multiple-hit vehicles. The swarm provides robustness to enduring enemy assaults.

Swarms may also utilize countermeasures to better ensure the survivability of the system and the completion of the mission objective. Utilizing swarms to attack enemy entities can vary from ranged targeting to vehicles delivering their equipped payloads with onboard system navigation.

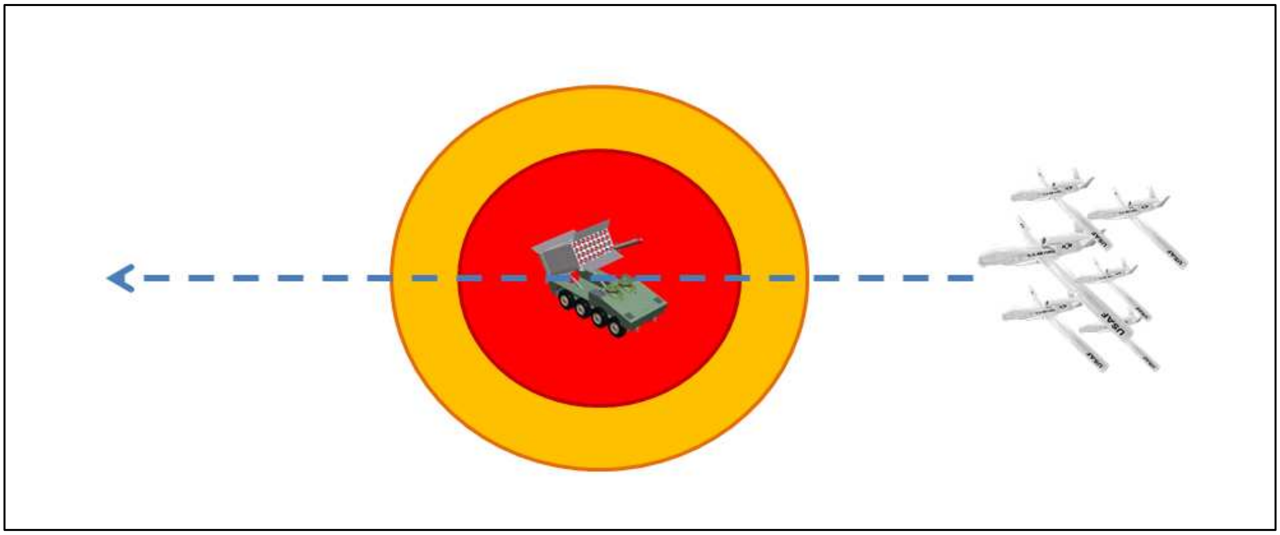

Figure 5. Swarm Approach [Erlandsson]

UAV and Aircraft Design for Survivability

Aircraft are historically designed using a requirements-driven design process: the required performance of the aircraft is known and components are assembled to meet the performance goals [Chakraborty]. Historically, AS requirements have been met either through the design of add-on technologies (such as armor, fuel tank inerting technologies, active countermeasures) or through complicated, integrated, and systemic aircraft design (for radar cross section minimization, thermal signature minimization, for maneuverability). This investigation concerns itself with the design of UAS aircraft performance characteristics and tactics. Survivability is heavily reliant on exposure to hostile threats, being either hit or within engagement range. By having a vehicle that is fast and armored, the aircraft will likely take fewer hits while being more likely to endure them [Soban]. Often a fast aircraft is not heavily armored due to the presence of stark design tradeoffs between weight, cruise speed, etc. [Melnyk] [Soban]. Today, the industry must rethink our approach to aircraft survivability to consider modern threats and counters. For instance, a swarm may be more effective to achieve a mission than one aircraft system due to highly effective single target anti-aircraft weapons. Traditionally, aircraft survivability considered mostly the ability to withstand damage [Ball]. Our approach seeks to provide more realism with exposure to an enemy entity.

Conclusions

Based on these observations, there exists a considerable gap in the understanding of the broader design space around the design of UAS for survivability. As aircraft survivability threats and technologies have advanced, aircraft survivability modeling concepts must do so as well. No research to date has defined the tradeoffs between the aircraft performance characteristics of UAS and modern survivability concepts including modern metrics, tactics and technologies. None of the survivability software suites are available for public inspection, validation and use under open-source science concepts. None of the aircraft survivability design concepts have been demonstrated to have utility to a UAS design process. This dissertation effort will seek to advance the state of knowledge in this field by addressing these gaps.

3. PROBLEM FORMULATION AND RESEARCH QUESTIONS

Based on the research challenges outlined in the previous chapter, a primary research question can be posed:

> The current aircraft survivability approach is driven to model hits on target and location of hit analysis (shot-line geometrics) [Ball] [Magister] [Yang]. The approach defined in this research seeks to provide more considerations to various important aircraft survivability factors. Our approach considers the time within engagement range of an enemy entity (lethal envelope) [Erlandsson] [Wang]. Also, we have applied various other advanced capabilities to engage with emerging threats. These considerations are digital pheromones, loyal wingman, and swarming [Frye] [Humphreys] [Wang]. All the combined analytic considerations provide a more robust and realistic understanding of aircraft survivability while preserving the value of traditional aircraft survivability approaches.
>
> Primary Research Question: ***Can UAS-specific aircraft survivability models be developed and integrated to facilitate aircraft and tactical analysis, design and optimization?***

To answer this question, this research effort will establish the methods and framework for physical and empirical parametric modeling of UAS-specific aircraft survivability

This research effort establishes the methods and framework for physical and empirical parametric modeling of UAS-specific aircraft survivability. Information from Robert E. Ball's approach regarding number of hits on aircraft relative to aircraft survivability has been gathered to develop a model that can be simulated and integrated with various other approaches (i.e. lethal envelope, digital pheromones, loyal wingman, swarm, etc.) [Ball] [Humphreys] [Wang]. Traditionally, aircraft survivability approaches apply to manned and unmanned air vehicles. With the considerations of advanced aircraft survivability counters: loyal wingman, digital pheromones, and swarming, this approach is for unmanned aircraft. Via literature research and conference interfacing, strengths and weaknesses of current aircraft survivability analyses have been identified. Also, a new aircraft survivability methodology for a more robust, modern, and realistic approach has been developed. A modeling and simulation framework for analyzing the new aircraft survivability methodology has been developed and implemented with verification and validation evidence. Sensitivity analysis to identify aircraft design parameters closely related to aircraft survivability has been used. The new aircraft survivability approach with the old in relation to aircraft design has been compared and contrasted.

The tasks associated with this research question can be defined as:

Task 1) Via literature research and conference interfacing, identify strengths and weaknesses of current aircraft survivability analyses.

Task 2) Develop a new aircraft survivability methodology for a more robust, modern, and realistic approach.

Task 3) Develop and implement modeling and simulation framework for analyzing the new aircraft survivability methodology.

Task 4) Verify and validate new aircraft survivability model.

Task 5) Use sensitivity analysis to identify aircraft design parameters closely related to aircraft survivability.

Task 6) Compare and contrast, the new aircraft survivability approach with the old in relation to aircraft design.

Research Question 1 – Regarding Model Development

The AS community would like to be able to consider the modeling of AS in early design stages of a UAV/UAS design process.[3] This first research question asks whether the design considerations for UAS can be modeled in a framework that allows for representation of the identified modern aircraft survivability tactics and scenarios.

Research Question 1: Can the tactics and performance of modern UAS be represented parametrically in an integrated and optimizable system model of Aircraft Survivability?

There are a number of challenges that are associated with answering this research question. Many of the concepts that are defined as making up modern UAS performance and operation have not been represented outside of the academic literature, so their efficacy and impact on aircraft design has not been quantified. The interactions between the components of the simulation are complex, multi-domain and time dependent. The software must be constructed to be open-source and computationally efficient to be able to allow optimizability and adoption by the community. The tasks associated with this research question can be defined as:

Task 1) Create baseline aircraft survivability framework and toolkit

Task 2) Create Open-Source implementation for AS community and military users

Task 3) Implement modern UAS-relevant tactics and performance models (Digital Pheromone method, Loyal Wingman, Swarm) [Sauter] [Humphreys] [Erlandsson]

Upon completion of these tasks, the integratability and optimizeability of the model will be supported if the models developed can be used to predict and optimize the survivability performance of a UAV under baseline and modern scenarios. If the design model can be used within a UAV design process to conceptually design and develop a UAS that meets design requirements, then the optimizeability and design process utility of the model will be supported.

Research Question 2 - Regarding Model Validation and Verification

With design models there exists a fundamental tradeoff between the fidelity of the design model and its usability in a computational design process. If the model is too refined, then the computational cost becomes too great for use in early stages of design. If the model is computationally efficient, but cannot predict the relevant design tradeoffs, then the model is of no value to designing among those tradeoffs. This research question seeks to understand the level of validation and verification that can be achieved using the models proposed.

> ***Research Question 2: Can the proposed aircraft survivability software and methods be validated and verified?***

Direct validation of aircraft survivability models has been complicated by the lack of data regarding "experimental" aircraft survivability datasets. For this effort, we will be unable to gather new datasets for aircraft survivability, and so we will develop a suite of analyses and comparisons to establish the level of trust that can be placed in the proposed models by practitioners. In order to have utility for design purposes, the design model must be of the correct scale in order to capture relevant design characteristics, but must not be bloated with irrelevant contributing analyses. This research question seeks to identify sensitive and relevant flight performance parameters for quantifying aircraft survivability metrics.

The tasks associated with this research question can be defined as:

Task 1) Documentation of verification procedures and data including approaches with descriptions of effectiveness and purpose.

Task 2) Documentation of validation procedures and data using methods of error estimation, comparison to previous models, and qualitative justifications.

Task 3) Model sensitivity analysis and justification of modeling scope

Upon completion of these tasks, this effort will be able to qualitatively and quantitatively defend the scope of the aircraft survivability model, and will be able to qualitatively and quantitatively understand the error of the simulation in modeling aircraft survivability metrics.

Research Question 3 - Regarding Model Application

The final aspect of this research is to demonstrate the utility of the models and considerations of aircraft survivability in improving the design of UAVs. This leads to the development of the third research question which incorporates result from the previous two research questions.

Research Question 3: What are the conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process?

This project asserts that the design of UAS can be improved towards metrics of aircraft survivability by including tactics, missions, and behavioral modeling of the UAS groups with a deeper understanding of aircraft survivability. This research question seeks to build a direct comparison of UAV/UAS design with and without these detailed aircraft survivability models. The results of this research question will quantify the differences between the aircraft design methods proposed in this work, and a default aircraft sizing and synthesis algorithm that uses naïve surrogates metrics of performance to approximate survivability. As seen by the analytics, aircraft cruise speed is very sensitive to aircraft survivability. Almost all aircraft design parameters are related and cruise speed indirectly influences various parameters including weight, thrust, lift, fuel efficiency, etc. Therefore, the conditions to where the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process are endless.

The tasks associated with this research question can be defined as:

Task 1) Identify sensitive aircraft survivability parameters with system sensitivity analysis

Task 2) Within an aircraft sizing algorithm, relate sensitive aircraft survivability parameters to generic aircraft design parameters.

Task 3) With identified related aircraft design parameters, make design changes utilizing each of the traditional aircraft survivability and the new approach.

Task 4) Compare and contrast traditional aircraft survivability analysis to the newer approach in relation to aircraft design.

Project Scope Definition

The purpose of this research is to enable design tradeoffs between aircraft design processes and inputs and the metric of performance of survivability for UAVs. With this tool, methods, tradeoffs made explicit, this now allows mission designers to trade other -ilities against survivability in ways that are not available before. Figure 6 outlines the described project scope in regards to UAV system design.

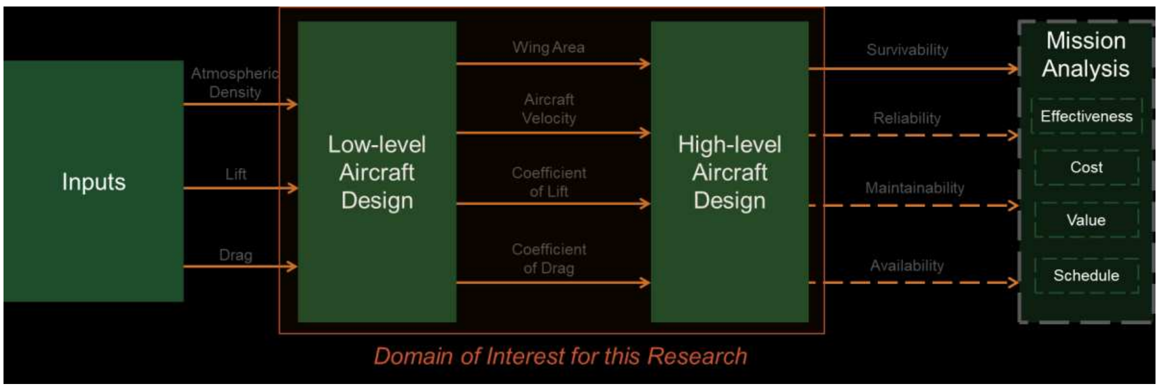

Figure 6. Diagram illustrating project scope in the context of aircraft design and system-level design activities including mission analysis

4. UAV SURVIVABILITY MODELING AND SIMULATION DEVELOPMENT

This chapter is about the development of the UAV survivability modeling and simulation. The chapter answers Research Question 1: Can the tactics and performance of modern UAS be represented parametrically in an integrated and optimizable system model of Aircraft Survivability? Previously, this chapter has been presented in this dissertation proposal. The UAV survivability modeling and simulation provides the base for other chapters to use. Within this chapter, UAV survivability is defined and modeled to be simulated for behavior observation. The methods presented are aircraft hits on target and the lethal envelope. By execution of the methods, killability and survivability are generated as results to answer Research Question 1.

Modeling and Simulation Development

In response to the tasks associated with Research Question 1, this research has first developed a modeling framework to simulate the tactics and performance of modern UAS parametrically using a system model of aircraft survivability. The proposed approaches apply the traditional survivability methodologies including hits on target and the lethal envelope, as well as more modern analyses including digital pheromones, swarming, and loyal wingman. These applications listed are diagramed in the various figures below. For hits on target, the aircraft survivability decreases as hits on targets increase. For lethal envelope, as the vehicle is within the envelope, the UAS is vulnerable to hits. The more modern approaches take into account dynamic scenarios for specialized encounters. Specific computational and conceptual models were developed and simulated to accurately measure aircraft survivability and identify related sensitive parameters.

The overall objective of the framework is to provide reasonable air vehicle design parameter feedback in regards to survivability to the user. In Figure 7, a high-level outline describing inputs and outputs to significant subsystems of the framework is diagramed. The initial input to the simulation is the performance of the air vehicle system and a specific scenario definition. These characteristics are input to one of the aircraft survivability analyses (as specified by the user). Outputs from the survivability analysis are the three primary survivability metrics (survivability, susceptibility, and killability). The air vehicle design analysis outputs significant aircraft design parameters related to aircraft survivability and sensitivity analysis is performed on the output parameters. The approach can be described as a stochastic multidisciplinary design and optimization (MDO) method. The output of this modeling is an uncertainty informed understanding of the tradeoffs between air vehicle design and survivability in a specific scenario.

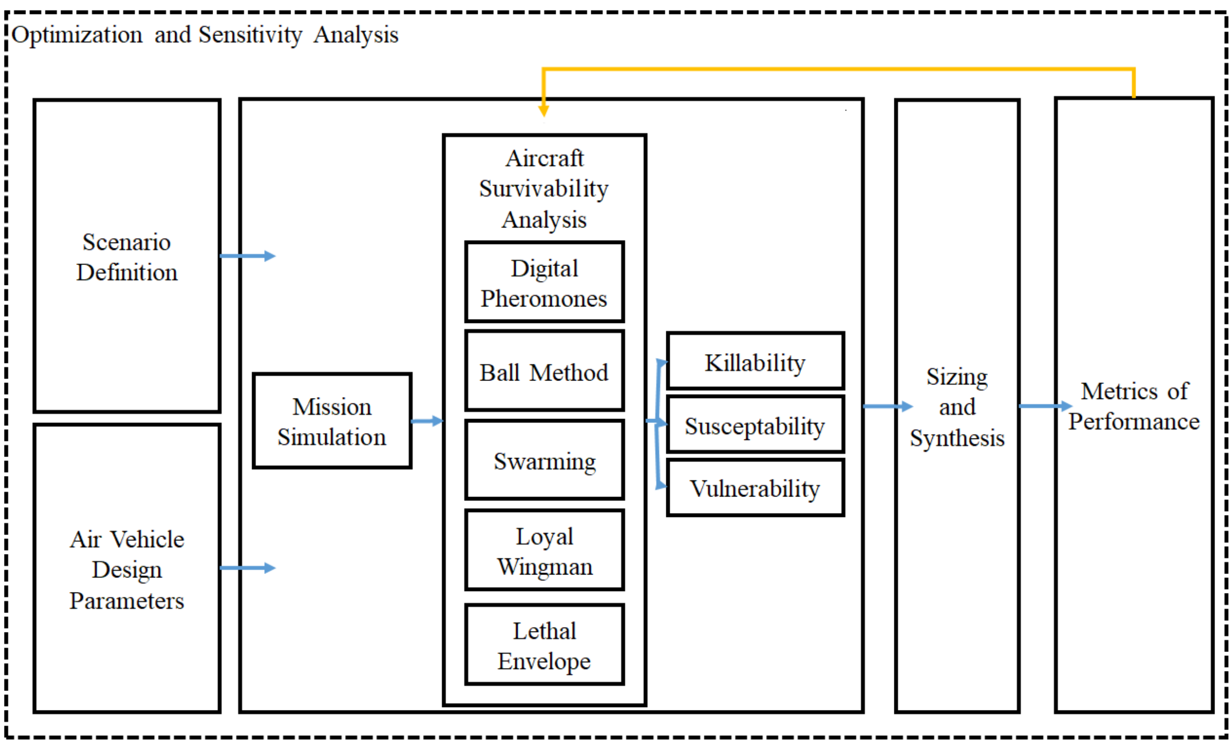

Figure 7. High-level Simulation Framework Flow Chart. Under the control of the user interface, the user can input scenario and design parameters for execution under one of the 5 survivability analyses. Under the option of optimizer control, the optimizer measures metrics of performance and optimizes the design of the aircraft to minimize objectives.

At highest level, the modeling and simulation tool has been organized into system architecture. Shown in Figure 8, the framework is comprised of analysis, scenarios, simulations, and a user interface (UI). Each item performs an important role for the overall functionality of the framework as shown in attributes and operations. Together, the simulation analyzes a scenario simulation specified with the user interface. There are more complexities within each block contributing to the entirety of the aircraft survivability framework.

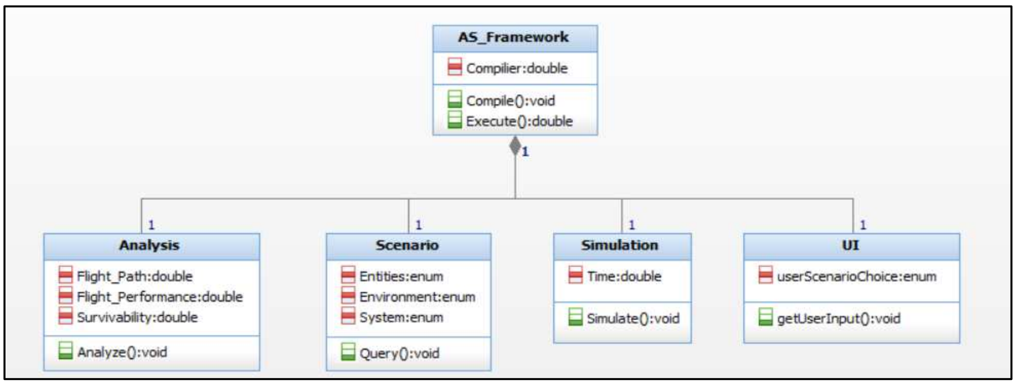

Figure 8. Architecture for the Modeling and Simulation

Aircraft survivability can be a challenging metric to quantify, this project provides an approach to calculating aircraft killability, the opposite of survivability. In doing so, previous predicted generic metrics and information to a detailed model are applied utilizing simulation with physical and statistical analytics. For this demonstration, verification and validation methods are used to predict the average killability for a Lockheed Martin C130J Super Hercules in a mission where the aircraft is hit at least once. As seen in Figure 9, the C-130J is a large cargo aircraft. One of the challenges with aircraft survivability is the lack of measured real world data. A C-130J was selected to be modeled and simulated due to its long history of combat service and its inherent flight performance that leads to a very high susceptibility to enemy attacks. Although a C-130J is not a UAV, it stands a strong basis for the aircraft survivability modeling and simulation to be applied to UAVs. Figure 9 shows an image of the C130J Super Hercules in flight. The C130J often enters hostile environments due to the larger landing approach of the aircraft [Jerome]. By predicting the C130J Super Hercules average killability, an understanding of a blind environment mission can be quantified.

Figure 9. Lockheed Martin C130J Super Hercules

In an aircraft survivability modeling sense, scenarios describe when and where the aircraft are exposed to hostile environments [Clothier]. When the opposition is mostly known, having a metric to predict the likelihood of aircraft survivability of any encounter has value. The realistic hostile environments are when an aircraft is exposed to enemy environment operations, ambush tactics, and guerilla warfare. For the United States military, these environments have been encountered regularly in recent times [Jerome]. As aircraft are valuable assets, having an understanding of the likelihood of aircraft survival is effective for military strategy, planning, support, and go-no-go decisions.

The model used is an aircraft survivability calculation from *Analytic Model for Aircraft Survivability Assessment of a One-on-One Engagement* by Xu Wang, Bi-Feng Song, and Yi-Fan Hu published in the Journal of Aircraft 2009 [Wang]. There are multitudes of considerations to generate the one-on-one engagement model and are too lengthy to be listed here, see the publication for any conceptual clarification. Some of the more relevant considerations are the number of hits on the aircraft, aircraft velocity, and lethal area [Couch]. In the Air Force Institute of Technology publication, an A-10 Warthog was arbitrarily chosen as the conceptual model aircraft, given its documented exposure to hits in operation [Melnyk]. Figure 10 and Figure 11 illustrates some aspects of the model used, where Figure 10 shows the geometry of the combat scenario and Figure 11 is the survivability equation. With this model embedded into the AirSurF simulation, aircraft survivability can be determined as a function of aircraft performance characteristics and scenarios characteristics.

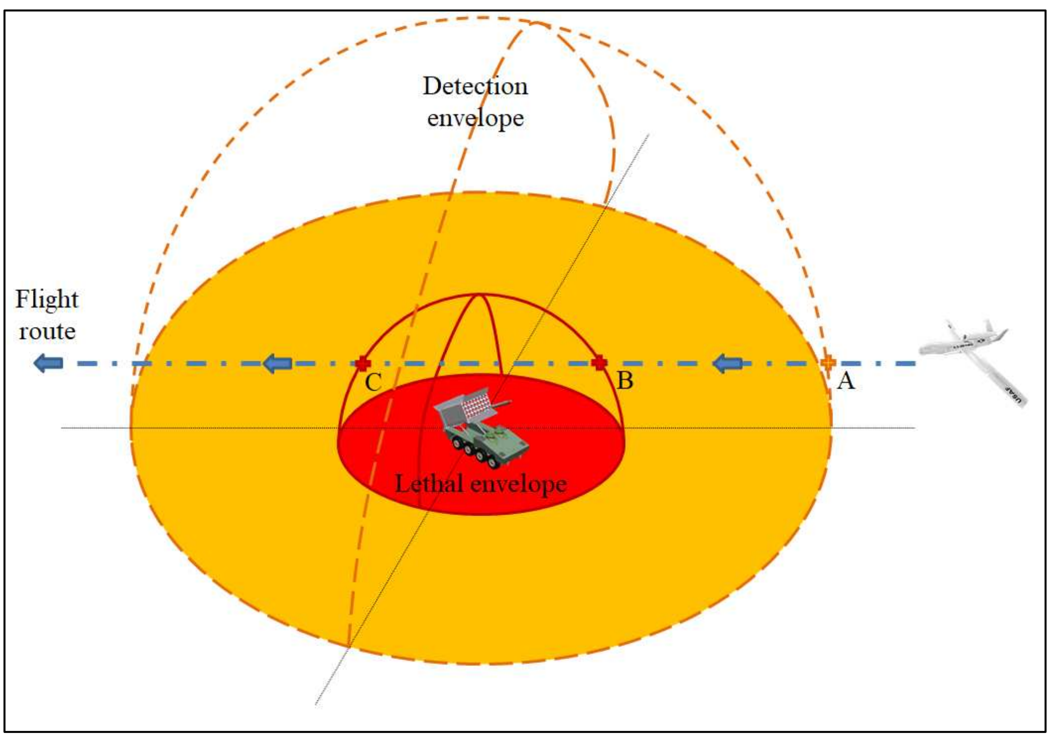

Figure 10. Aircraft Scenario [Wang]

$$
\begin{aligned}
P_s &= e^{-(s_2-a)r_d} + \frac{1}{2}\sqrt{q_{SSK}}\, r_d e^{-r_d(s_2-a)} \\
&\times \left[\left(1+\sqrt{q_{SSK}}\right) \frac{e^{(s_2-s_1)\beta}-1}{\beta} - \left(1-\sqrt{q_{SSK}}\right) \frac{e^{(s_2-s_1)\gamma}-1}{\gamma} \right] \\
&+ \sqrt{q_{SSK}}\left(1-e^{-(s_1-a)r_d}\right) e^{-2r_k(s_2-s_1)} \left[sinh\left(2r_k\sqrt{q_{SSK}}(s_2-s_1)\right) \right. \\
&\left. + \sqrt{q_{SSK}}\, cosh\left(2r_k\sqrt{q_{SSK}}(s_2-s_1)\right) \right] \qquad a < s_1
\end{aligned}
$$

Figure 11. Aircraft Survivability Equation [Wang]

$$\beta = r_d - 2r_k\left(1-\sqrt{q_{SSK}}\right)$$

Figure 12. Beta Equation

$$\gamma = r_d - 2r_k\left(1+\sqrt{q_{SSK}}\right)$$

Figure 13. Gamma equation

Figure 11 defines the Aircraft Survivability Equation, P_s, for a lethal envelope scenario. Within the equation are a plethora of variables, including s_1, the time the aircraft spends within the detection envelope. Variable s_2 is the time the aircraft spends within the lethal envelope. Variable a is the time the hostile entity acquires the presence of the aircraft, tracks, and obtains a firing solution. The reciprocal of the mean time of detection is represented by r_d. Variable q_{SSK} is the single shot survivability. The average rate of fire is represented by r_k. Figure 12 and Figure 13 represent variables used within the Aircraft Survivability Equation of Figure 11. The listed variables can calculate total aircraft survivability.

The data acquired is from *The Fundamentals of Aircraft Combat Analysis and Design* by Ball, Robert E. from the AIAA Educations Series 1985 in which the means to the data acquisition is unknown [Ball]. From either experiments or an analytical model, the data will be treated as experimental. The provided data is aircraft killability in relation to aircraft exposure to hits. The range of hits of an aircraft is provided as 1 to 30 for redundant aircraft and 1 to 18 for nonredundant aircraft. The C130J computational model is likely to have many redundancies. However, both the redundant and nonredundant killabilities were measured in the likelihood of the C130J being a hybrid aircraft of both redundant and nonredundant subsystems. As aircraft survivability is less experimental and more predictive, the provided data is used and compared to the referenced engagement model. Input data and parameters are extensive including the lethal area, time detected, aircraft velocity, etc. The variations of inputs for the Monte Carlo simulation are the aircraft velocity and the number of hits. Where the variation of input for the MDAO simulation is the detection time, detection and lethal area time, and reload fire rate. As seen in Figure 14, redundant or non-redundant aircraft killability greatly increases per hit. The exposure to multiple or one hit(s) is compared and used in the prediction of a C130J Super Hercules average killability.

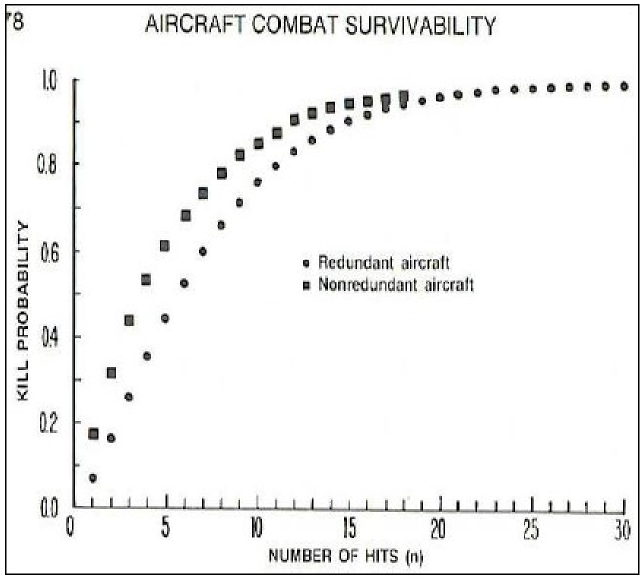

Figure 14. Aircraft Combat Survivability [Ball]

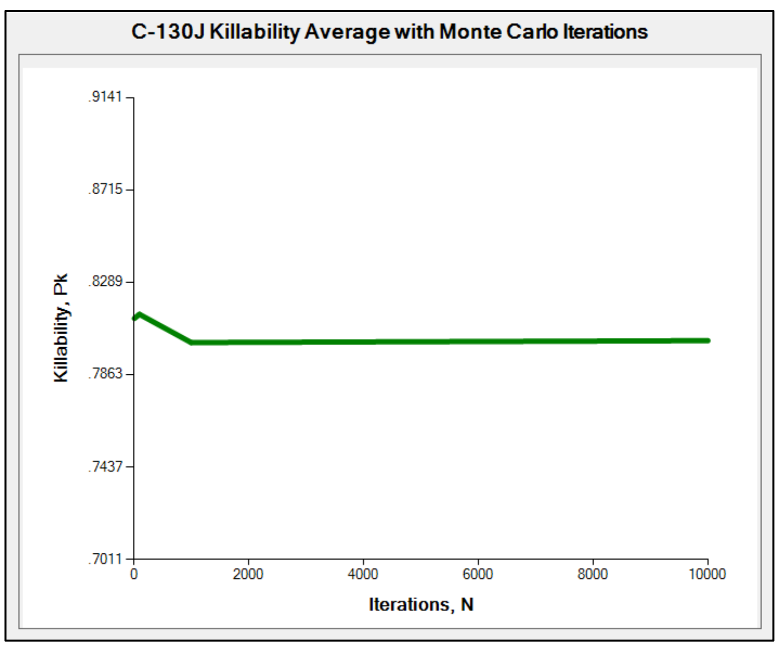

Figure 15. C-130J Killability Average

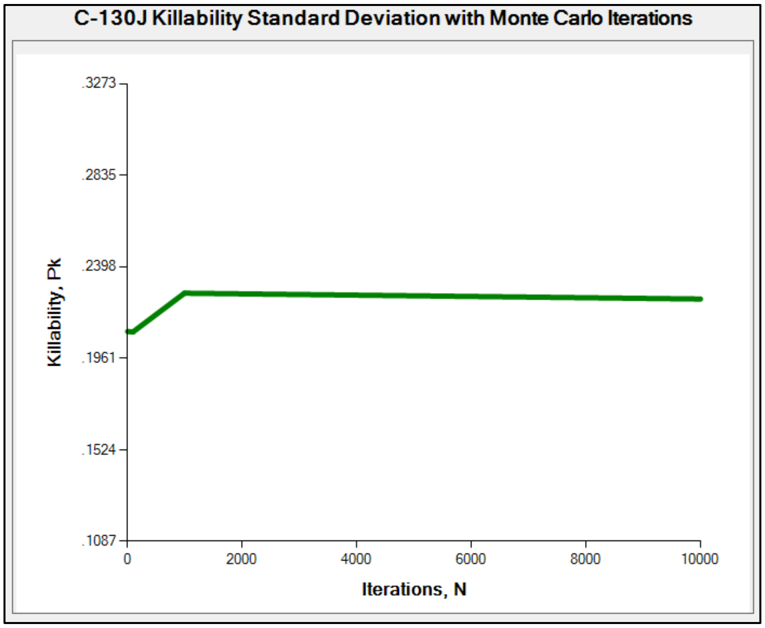

Figure 16. C130J Killability Standard Deviation

The observed model and scenario would be described as Normal mode, consisting of traditional approaches and no emerging threat methods. Normal Mode's traditional aircraft survivability analysis is comprised of Ball's hits on target and Wang's lethal envelope. Specifically in the example scenario, the survivability implications of a C-130J entering the lethal envelope of a MANPADS, is shown. In Figure 15, the killability average can be seen and in Figure 16 the killability standard deviation is shown, both with Monte Carlo iterations. As seen from the Monte Carlo simulation, the average killability of a C130J Super Hercules for any mission exposed to hostilities is ~0.80 with a standard deviation of ~0.22. Other scenarios were developed to consider more threats and different air vehicles.

- Digital Pheromone (Avoid dangerous areas)
- Loyal wingman (Escort vehicle, intercept, defend, and/or attack hostiles)

- Swarm (System level aircraft survivability)
- Blended DP/LW (Avoid areas with loyal wingman)
- Blended DP/S (Avoid areas as a swarm)
- User Interface Scenario Mode Selection

Countermeasures Modeling

In traditional aircraft survivability, the ability to withstand hits is measured without considering the capability of neutralized an enemy threat. Many air vehicles are equipped with defensive munitions. In a case-by-case scenario, the munitions may be used to eliminate enemy threats. By utilizing countermeasures to remove the possibility of attacks hitting the aircraft, the overall aircraft survivability will improved. Countermeasures are an AirSurF simulation option for specific scenarios.

To conduct the study, a framework tool was developed and referred to as AirSurF. The user selects the scenario, mode, and scenario specifics. Figure 17 shows the User Interface (UI) to selecting the scenario mode. As shown, each mode represents one or multiple emerging threat considerations. The AirSurF utility is intended to be open-source with this project. Having a tool to conduct the analytics was irreplaceable for acquiring results.

```
Select scenario mode
-------------------------------------
1) Normal
2) Digital Pheromone
3) Loyal wingman
```

Figure 17. AirSurF User Interface

This chapter answers Research Question 1: Can the tactics and performance of modern UAS be represented parametrically in an integrated and optimizable system model of Aircraft

Survivability? The chapter discussed the implications to developing the survivability model and survivability methods integrated into the model. UAV survivability results were presented from example test cases. Through the survivability results, Research Question 1 can be answered as this chapter shows the tactics and performance of modern UAS are represented in an integrated and optimizable system model of Aircraft Survivability. With an effective survivability model, survivability in relation to UAV tactics and design can be further investigated and understood.

5. UAV SURVIVABILITY MODEL VERIFICATION AND VALIDATION

This chapter seeks to inform and defend the verification and validation of the UAV survivability model. The chapter answers Research Question 2: Can the proposed aircraft survivability software and methods be validated and verified?

Verification and validation of the UAV survivability model ensures reliability and clarity in the results presented within this dissertation. In this chapter, the model is verified and validated through a combination of qualitative methods and quantitative error propagation and system sensitivity analyses.

The modeling of engineering systems and validation of these models presents difficulties when compared to modeling and validation techniques that are used under traditional engineering sciences paradigms. For example, survivability models for multi-vehicle UAV fleets does not have any readily available datasets that can be used to compare the performance of the modeling performed in this research to "ground truth". Instead, new approaches, frameworks, and theories, need to be developed and applied to understand the validity of engineering systems' modeling and decision making.

In the context of this research we will define model validity as a determination of the degree to which the model is an accurate representation of the real world from the perspective of the intended uses of the model. As defined in the problem formulation and research questions discussion, the purpose of this model is to define survivability tradeoffs within the proposed aircraft design process. For this (and many other systems engineering applications) quantitative validation through comparison to experiment is not available, so validation must be performed by amassing evidence of validity. [Mitre]

- Validation exercise 1: One activity performed is comparison to other models to which the survivability model itself is able to replicate exactly the results from Wang, et al., under identical scenarios/parameter values.
- Validation exercise 2: Another method performed is parameter variability and sensitivity analysis of which the survivability model is able to qualitatively replicate expected direction and magnitudes of response for the metric of survivability as a function of all inputs.
- Validation exercise 3: Lastly, the final activity performed is face validity to where this model and its results were presented at 5 secure and public conferences, and in Journal of Defense Modeling and Simulation where experts were explicitly asked whether the model and/or its behavior are reasonable.

Each validation activity performed aligns with the Systems Engineering and Aerospace Engineering recommended validation approaches for modeling of complicated systems Together, these illustrate that the model is fit for purpose, and valid for use in defining aircraft survivability design tradeoffs.

Verification and Validation

Supporting the Monte Carlo uncertainty analysis, CDFs and their inverses are calculated. Figure 18 and Figure 19 show the CDF and inverse CDF of the measured number of hits. Whereas Figure 20 and Figure 21, show the CDF and inverse CDF of the Experimental Error in regards to the simulation. In addition, the sensitivity is seen and considered from the Kline McClintock calculations comprised of the experimental and validation errors. The largest error into to the Monte Carlo killability prediction is the model error. The tool error is relatively small. There, the killability variance can be seen as sensitive to the number of hits on the aircraft. With analysis, a variance in the aircraft cruise speed would influence the aircraft killability slightly. Cruise speeds for aircraft are consistent and vary little. Otherwise, the aircraft killability is slightly sensitive to aircraft velocity uncertainty [Erlandsson]. Figure 22, 23, and 24 show the histograms supporting the aircraft killability Monte Carlo analysis. Another MDA simulation sheds more information to the C130J killability.

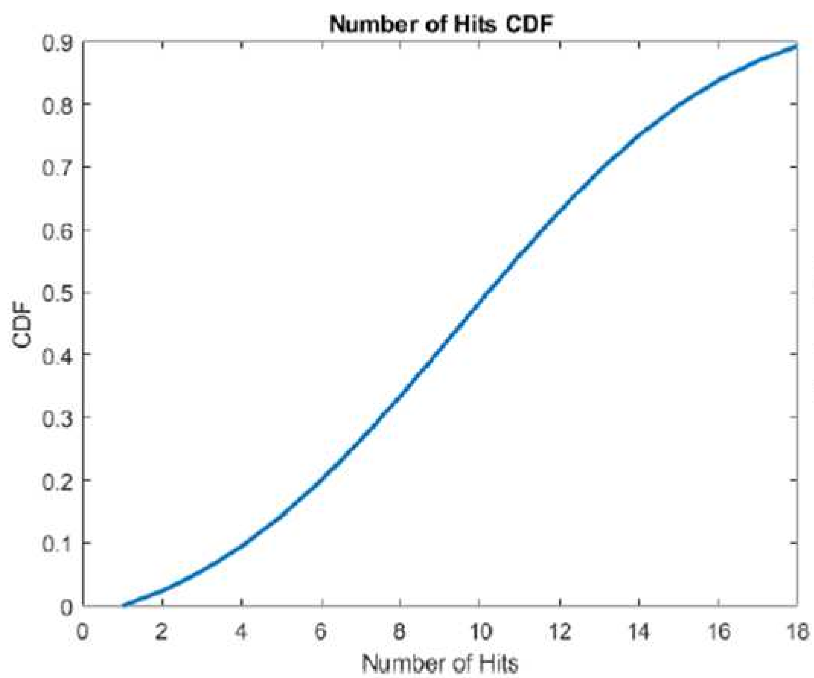

Figure 18. Number of Hits CDF

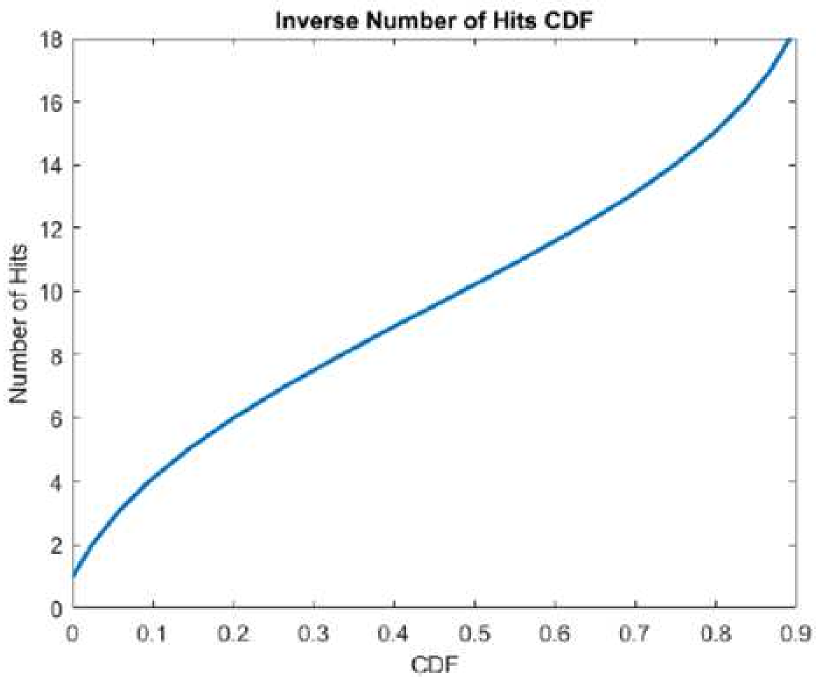

Figure 19. Inverse Number of Hits CDF

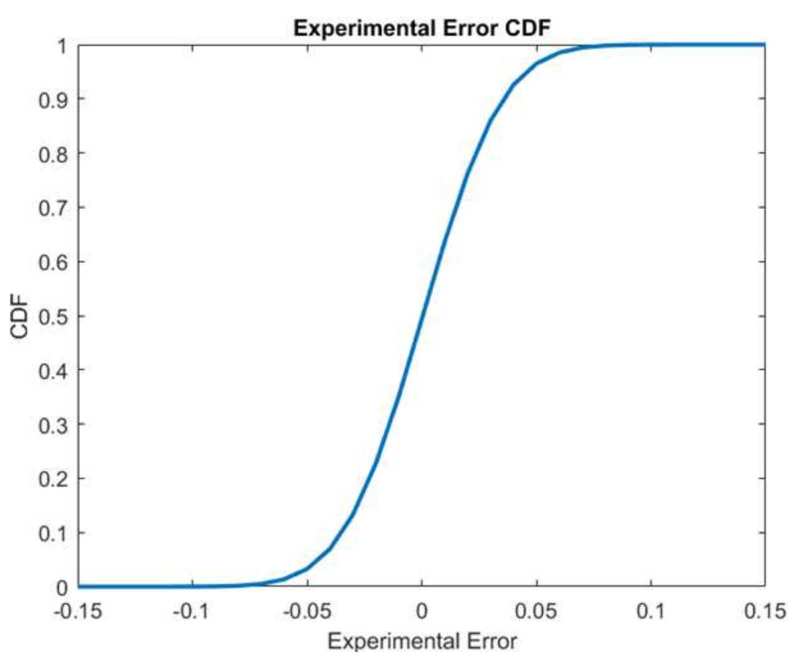

Figure 20. Experimental Error CDF

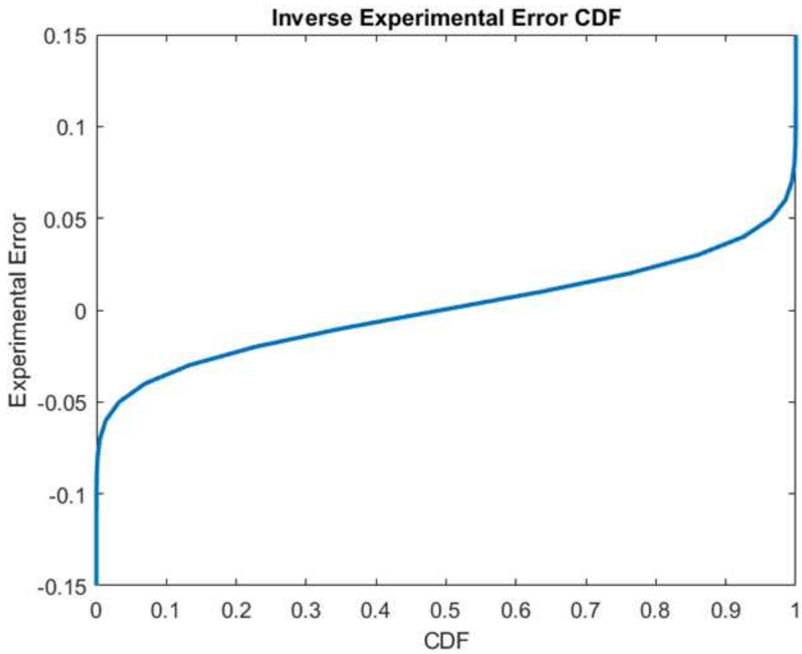

Figure 21. Inverse Experimental Error CDF

As can been seen from the killability error, the model and provided killability of an aircraft are somewhat similar. The decent size error is enough to suggest the model is verifiable. Figure 20 and 21 display the CDF and inverse CDF of the experimental error. Some other uncertainties could be the various other inputs (i.e. lethal area, time detected, etc.) [Erlandsson]. For comparison, many inputs were chosen to emulate one hostile entity for the model verification and the C130J simulation. Uncertainty in the hostile entity capabilities could greatly influence the aircraft killability (i.e. large lethal envelope, fast fire rate, etc.). With the moderate killability and experimental error, the model can be stated as verified from an error perspective.

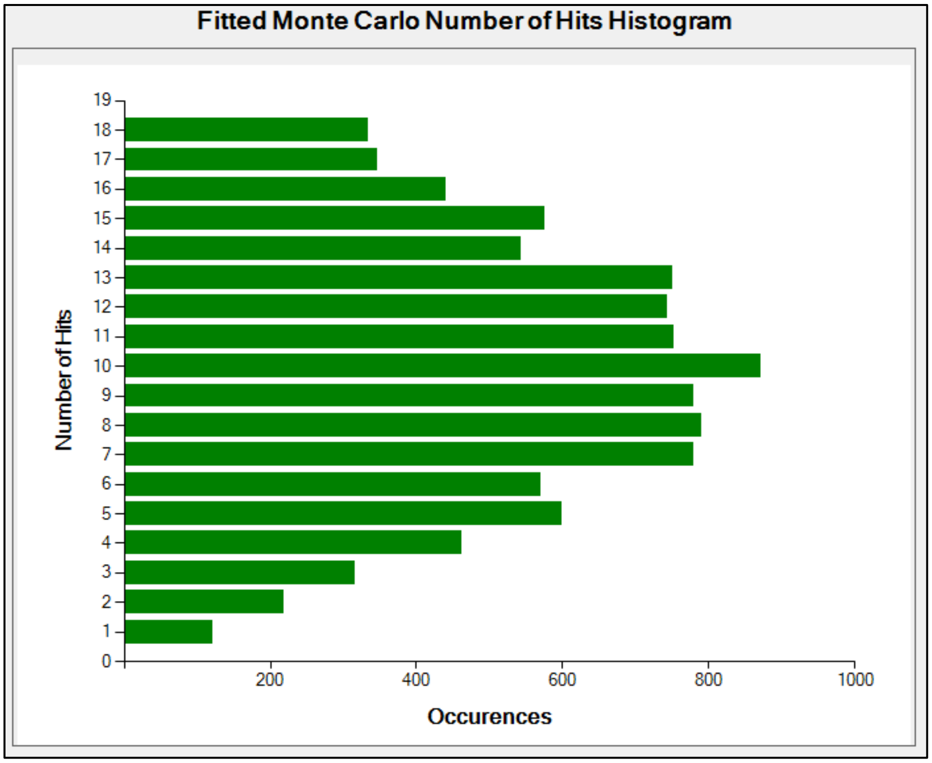

Figure 22. Monte Carlo Number of Hits Histogram

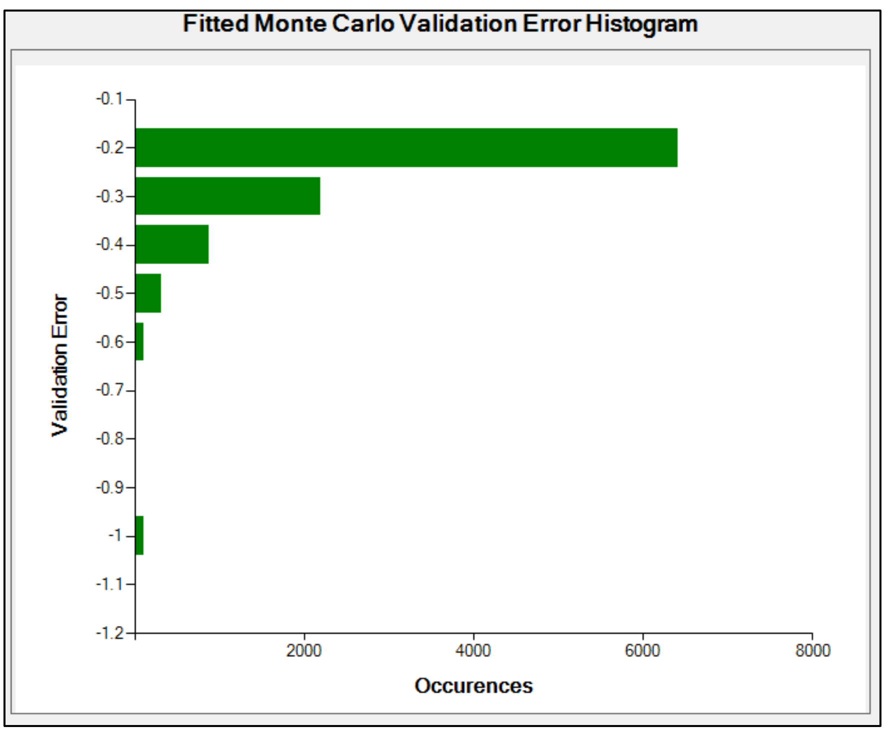

Figure 23. Monte Carlo Validation Error Histogram

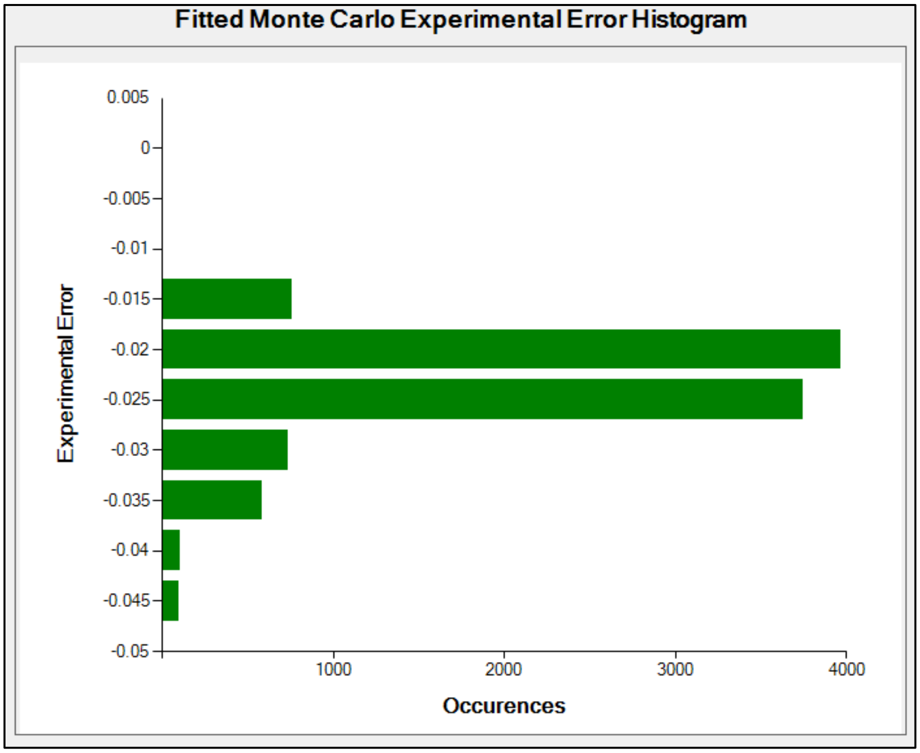

Figure 24. Monte Carlo Experimental Error Histogram

The histograms of the Monte Carlo method describe various distributions for input and output parameters. In Figure 22, the Number of Hits Histogram is a relatively normal distribution. Also, the Validation Error, seen in Figure 23, seems to be an exponential distribution skewed right. The Experimental Error in Figure 24 is more so a normal distribution, skewed left. Each distribution was used to conduct the Monte Carlo application on the model. By observing the distributions, some insight to the Monte Carlo approach is observed.

Error Propagation and Estimation of Bias Error

This project intends to report model uncertainties effectively with minimal concessions to inaccuracy. An accepted method of uncertainty measurement is the ISO/ANSI approach, where Type A uncertainties are estimated with sampling and Type B uncertainties are estimated without sampling [Oberkampf]. Kline McClintock approach enables the combination of the two estimations. The Kline McClintock merge of ISO/ANSI method is used for uncertainty measurement and is shown in Figure 25. Without correlation and dependence, the first-order Kline-McClintock propagation of uncertainty for a $x = f(u,v)$ equation is shown in Figure 26. The listed propagation of uncertainty approach is effective for simple and easily differentiable equations. For more challenging equations, the derivative can be approximated or Monte Carlo utilized. In the case of type B uncertainties, the uncertainty can be estimated with the un-sampled uncertainties using the sum of the square of the standard deviation [Kline]. The Kline-McClintock equation can be expanded out to support uncertainty propagation.

$$\sigma_x^2 \cong \sigma_u^2 \left(\frac{\partial x}{\partial u}\right)^2 + \sigma_v^2 \left(\frac{\partial x}{\partial v}\right)^2 + \cdots$$

Figure 25. Kline-McClintock equation [Moffat]

The first order Kline-McClintock equation shown in Figure 26 provides a basis to applying uncertainty propagation measurement. Where x is the vector of design variables, y is the vector output of the CA, and σ^2 is a variance. An expansion of equations follows to make the Kline-McClintock more effective for simpler applications. In Figure 27, a model input and output in reference to the $x = f(u,v)$ equation is displayed. For a more practical equation, Figure 28 is the Kline McClintock equation with uncertainty and Figure 29 is another simplified form the Kline McClintock equation in first-order. In the shown equations, L is represented as an uncertain input and all the models are deterministic. Now to consider uncertainty, Figure 30 is the previous model diagram with an uncertainty update. With uncertainty taken into account, the Figure 26 Kline-McClintock equation is updated as shown in Figure 28. To again simplify the equation, the Kline McClintock with uncertainty reduces into another first order Kline McClintock equation with uncertainty in Figure 29 [Kline]. Variable T represents a simulation tool vector. The Kline McClintock approach producing uncertainty shown supports the reported model sensitivity results.

$$\sigma_v^2 = \sigma_L^2 \left(\frac{\partial T}{\partial L}\right)^2$$

Figure 26. First-order Kline-McClintock equation [Kline]

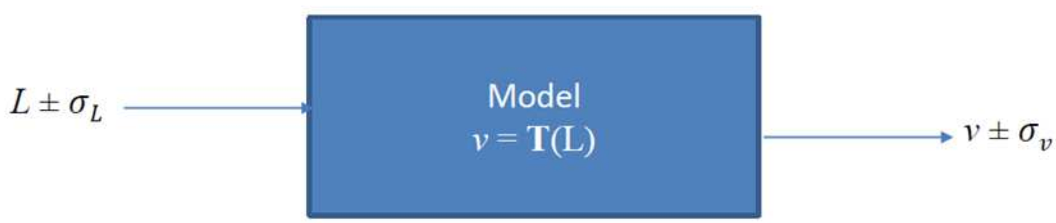

Figure 27. Model input and outputs [Kline]

$$\sigma_v^2 = \sigma_T^2 \left(\frac{\partial v}{\partial T}\right)^2 + \sigma_L^2 \left(\frac{\partial v}{\partial L}\right)^2$$

Figure 28. First-order Kline-McClintock equation with uncertainty [Kline]

$$\sigma_v^2 = \sigma_T^2 + \sigma_L^2 \left(\frac{\partial T}{\partial L}\right)^2$$

Figure 29. First-order Kline-McClintock equation with uncertainty reduced [Kline]

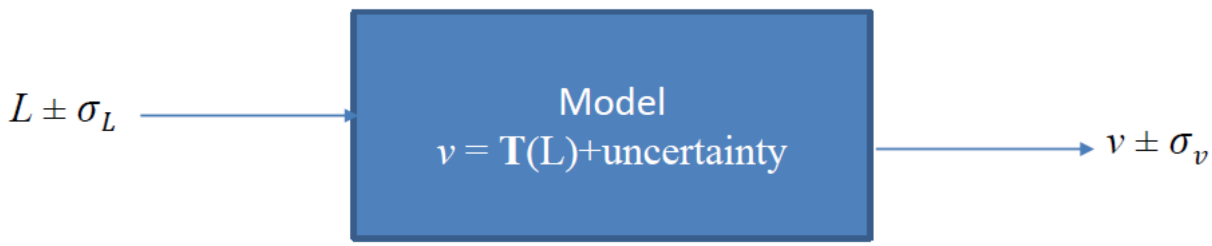

Figure 30. Model input and outputs with uncertainty [Kline]

The Kline-McClintock approach in conjunction with the Monte Carlo iterations produced relatively reasonable results for uncertainty. Each result for uncertainty supports the model sensitivity analysis. The estimated killability model average relative error is reported at 4.54% +/- 8.67% @ 90% CI. Survivability is a difficult metric to quantify the report relative error is acceptable in general nonetheless reasonable for aircraft survivability [Erlandsson]. The measured number of hits uncertainty average relative error is reported at 0% +/- 0.169% @ 90% CI. A minuscule average relative error is self-evident as acceptable. The reported total tool variance is 0.00826, a small variance. Finally, total Kline McClintock uncertainty is reported as 2.63, again a small and reasonable result. In whole, the uncertainty approach was appropriate for producing uncertainty measurements effectively. The results produced were verified as accurate at conference discussions with industry community. With the appropriate approach reviewed and community support, the model sensitivity analysis results are viewed as acceptable.

System Sensitivity Analysis Approach

To support the MDO objective, a multidisciplinary analysis (MDA) is applied to the complex system at a system level. Design points are specified as a number of design variables input to the MDA. Decomposed into disciplinary contributing analyses (CA), the MDA connects to form a design system matrix (DSM). With the MDA connected, the DSM structures information flow between CAs to form a system of coupled compatibility equations as the CA perform the analyses. Compatibility equations are typically used for iterative schemes as applied in this project's approach, ensuring CA variable values are compatible. The aircraft performance is improved with an embedded DSM within an optimization routine, varying input design variables and minimizing a cost function [Schaffer].

In the MDA approach, there are a few uncertainties accounted for: uncertainty from design variables and uncertainty from the CAs. Often, design variables add to system uncertainty from measurement inaccuracies. For the CAs, there are two sources of uncertainty: assumptions and deterministic computing models. CAs are essentially low fidelity approximations to reduce computational expenses and their discrepancies are measured as an uncertainty output. Also, the deterministic models are not capable of capturing stochastic variation of a component performance with accuracy. These uncertainties within the models are referred as computational noise [Darulova] [Trucano]. By involving feedforwards and feedbacks within the DSM, uncertainty can be increased or decreased nonlinearly at the converged design performance.

This project's approach to uncertainty propagation uses a Monte Carlo with MDA system sensitivity analysis. The MDA approach takes design variables and CAs and assigns them to uncertainties from uncertainty distributions. An approximation of a design point is acquired through iterations. This approach uses state variable vector output of the analysis (y), simple finite deviations (Δy), vector of design variables (x), and simulation tool vector (T) [McDonald]. Also, n represents the number of CAs and m represents the number of inputted design variables. From there, the Local Sensitivity Vector (LSV), as seen in Figure 31, is generated [Moffitt]. The LSV represents partial derivatives of the CAs with respect to the design variables. By having the LSV, the total propagated uncertainty can be estimated [McDonald].

$$[LSM][GSV] = [LSV] \equiv \begin{bmatrix} I_1 & -\frac{\partial T_1}{\partial y_2} & \cdots & -\frac{\partial T_1}{\partial y_n} \\ -\frac{\partial T_2}{\partial y_1} & I_2 & & \vdots \\ \vdots & & \ddots & -\frac{\partial T_{n-1}}{\partial y_n} \\ -\frac{\partial T_n}{\partial y_1} & \cdots & -\frac{\partial T_n}{\partial y_{n-1}} & I_n \end{bmatrix} \begin{bmatrix} \frac{dy_1}{dx} \\ \frac{dy_2}{dx} \\ \vdots \\ \frac{dy_n}{dx} \end{bmatrix} = \begin{bmatrix} \frac{\partial T_1}{\partial x} \\ \frac{\partial T_2}{\partial x} \\ \vdots \\ \frac{\partial T_n}{\partial x} \end{bmatrix}$$

Figure 31. LSV equation [Sobiezczanski-Sobieski]

From acquiring the total propagated uncertainty, individual contributions of uncertainty can be identified. In Figure 32, the equation for total propagated variance can be seen. In Figure 32, σ_s represent uncertainties for specific variables. With the total propagated variance, individual propagated uncertainty can be acquired [Moffitt]. Shown in Figure 33, the propagated contribution of uncertainty for either specific CAs or uncertainty of the inputs is illustrated. The listed uncertainty approaches are used to generate the system sensitivity analysis.

$$\begin{bmatrix} \sigma y_1^2 \\ \sigma y_2^2 \\ \vdots \\ \sigma y_n^2 \end{bmatrix} = (LSM^{-1})^2 \left(\begin{bmatrix} \sigma T_1^2 \\ \sigma T_2^2 \\ \vdots \\ \sigma T_n^2 \end{bmatrix} + (LSV)^2 \begin{bmatrix} \sigma x_1^2 \\ \sigma x_2^2 \\ \vdots \\ \sigma x_m^2 \end{bmatrix} \right)$$

Figure 32. Total propagated uncertainty [Sobiezczanski-Sobieski]

$$\bar{\sigma}_j = \frac{\sqrt{\sum_{i=1}^{n+m} \sigma_i^2}}{\sum_{i=1}^{n+m} \sigma_i} \sigma_j$$

Figure 33. Contributions of uncertainty [Sobiezczanski-Sobieski]

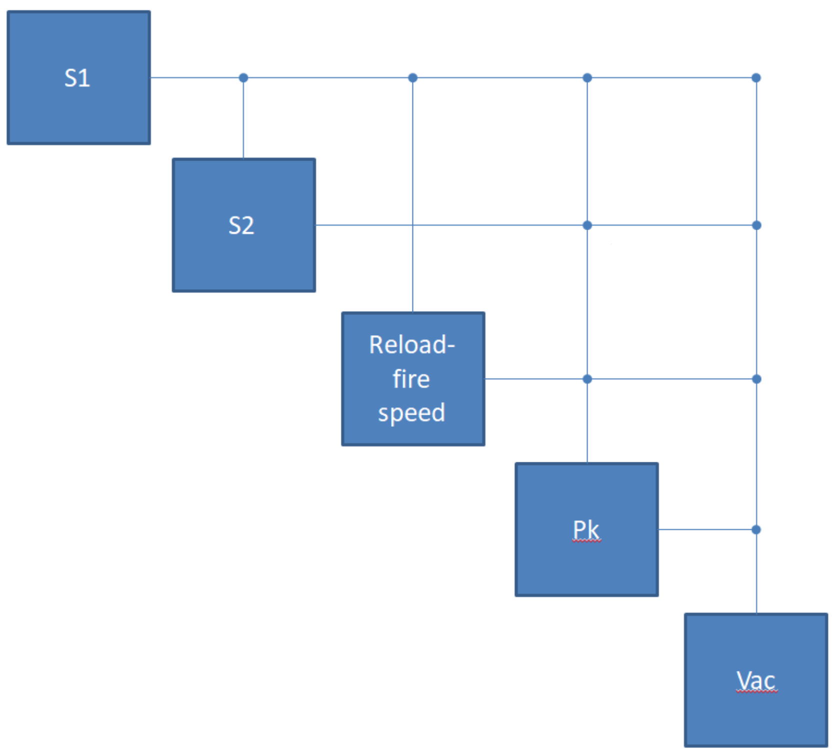

Figure 34. Design System Matrix

With the sensitivity analysis, comes the application where variance errors are related to Design and CAs. In Figure 34, the MDAO approach is mapped displaying different CA variables to other CA variables to be applied in an iterative fashion. Each relationship between the CA variables is diagramed as circular nodes. The cascading process shows S1, S2, and Reload-fire speed dependent on Vac and influencing Pk. For instance, after Pk is calculated, Vac can be calculated and input to the previous variables, establishing an iterative approach. The diagram is executed until fulfilling a satisfactory convergence criterion. In Figure 35, each CA variables is listed with inputs and outputs as well as relevant fractional errors. With the application, came reasonable system sensitivity results.

CA Number	**1**	**tool1**	**<Tool 1>**	
x inputs	*CA inputs*	*CA outputs*	*fractional error in design variable*	*Fractional error in CA output*
Vac		s1	0.05	0.1
CA Number	**2**	**tool2**	**<Tool 2>**	
x inputs	*CA inputs*	*CA outputs*	*fractional error in design variable*	*Fractional error in CA output*
Vac		s2	0.05	0.1
CA Number	**3**	**tool3**	**<Tool 3>**	
x inputs	*CA inputs*	*CA outputs*	*fractional error in design variable*	*Fractional error in CA output*
Vac		reloadFire	0.05	0.1
CA Number	**4**	**tool4**	**<Tool 4>**	
x inputs	*CA inputs*	*CA outputs*	*fractional error in design variable*	*Fractional error in CA output*
numberHits	reloadFire	Pk	0.05	0.2
	s1			
	s2			

Figure 35. Design and CA Variance Errors

The next efforts of this project are to define exactly how the Vac is going to be attained from Pk. Most likely, the aircraft will be sized using traditional aircraft sizing techniques. In aircraft design, Vac is an important and present variable. By acquiring Pk and desiring a target Pk, the Vac can be modified, thus altering the entire aircraft design. From there, iterations can improve and alter the aircraft design to improve Pk. In result, aircraft design can benefit from a modern perspective of aircraft survivability plugged into current aircraft design applications.

System Sensitivity Results

In a multidisciplinary analysis (MDA) simulation, the s1 (detection time), s2 (detection and lethal envelope time), time to reload and fire, and killability are calculated where the C130J velocity and the average number of hits are design variables. In a system sensitivity analysis using a modified MATLAB script developed by Blake Moffitt and Dr. Thomas Bradley, the s2 contributing analysis has the largest time variance compared to s1 and the reload and fire time [Moffitt]. The time variances can be seen in Figure 36. Where, the killability has a large influence from the s2 variance as well in reference to Figure 37. The output declares the killability has the largest uncertainty fraction of .4924 from the accumulation of uncertainties. The errors from each design variable were chosen in reference to variation in aircraft speed, time accuracy, and the verification and validation errors as seen in Figure 35. With the sensitivities considered and presented, the MDA is less optimistic than the Monte Carlo methodology claiming a killability of 0.7862 when exposed to 10 hits. Each simulation has a decent indication of likelihood for the C130J killability from exposure to hits. Having system sensitivity in regards to aircraft survivability measured enables an iterative relationship with aircraft design.

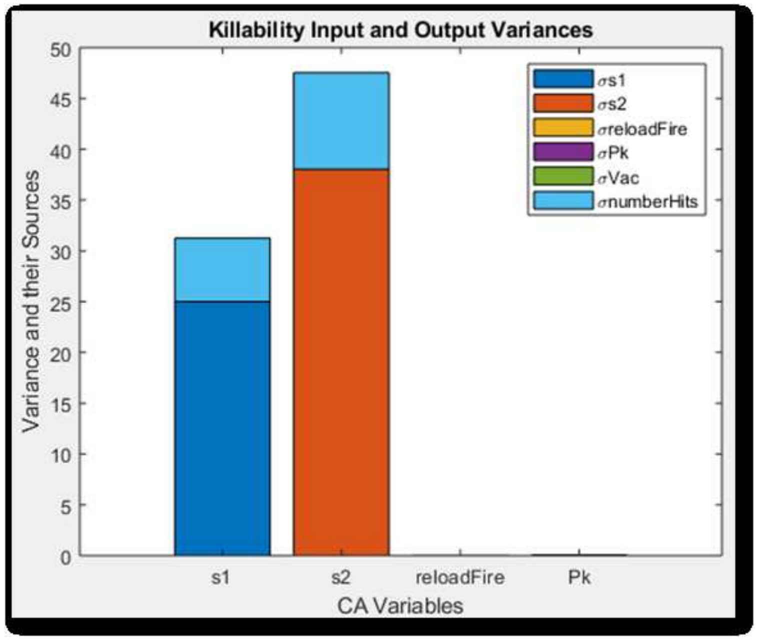

Figure 36. Killability Variances

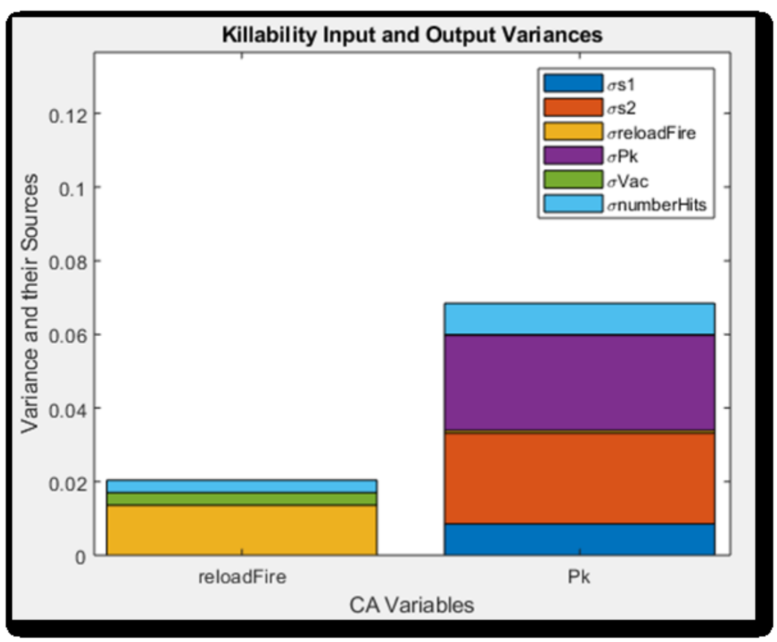

Figure 37. Reload and Fire Variance

Aircraft Survivability Related to Aircraft Design

The overall aircraft sizing approach is intended to intake aircraft survivability parameters and output important aircraft design metric values. By having a model and system sensitivity analysis, the aircraft survivability parameters can be related to aircraft design parameters in an iterative fashion. The established iteration relation can form a more solidified output in a Monte Carlo methodology with convergence [Darulova]. Together aircraft survivability parameters' iteratively produced can identify important and sensitive aircraft design metrics [Gu]. Having modern aircraft survivability analysis related to aircraft design, produces effective and reasonable aircraft design sensitivity analysis.

As can be seen in the Survivability Equation in Figure 11, there are higher order terms, possibly suggesting a non-linear system sensitivity analysis. A linear system sensitivity analysis was performed on the system model. The justification of the linear sensitivity analysis approach will be observed in the UAV design results as the design change suggestions are within a reasonably linear parameter space. It is suggested that future work could expand upon the presented sensitivity analysis for some further accuracy, but these yields would be minimal and would address design space parameters that are likely infeasible and not realistic to applicable UAV design. The results presented within Unmanned Aerial Vehicle Design Consideration Using Metrics of Survivability support the linear system sensitivity analysis presented.

With modern aircraft survivability analysis, various aircraft design parameters can be reviewed and better understood. Some important parameters for aircraft design are cruise speed, endurance, wing area, mass of aircraft, etc. [Kroo]. The relation of aircraft survivability to aircraft design can improve the aircraft design process by provided more effective aircraft design analysis [Raymer]. For instance, the duration of an air vehicle within the lethal envelope has a direct effect on the aircraft survivability. The design parameter of cruise speed is directly related to time within the lethal envelope. The iterative approach will more effectively gather evidence to support each aircraft design parameter's sensitivity to aircraft survivability [Soban]. An aircraft survivability centric approach to aircraft design improves an aircraft design to one of the most coveted aircraft metrics, aircraft survivability.

Conclusions

As threats have advanced, aircraft survivability has opportunities to consider newer challenges. Looking back on the past, Ball opened the world to reliable aircraft survivability analytics and is still effective as well as useful today. Now, we can shepherd that effort forward to combat newer threats with accurate representation of aircrafts' encounters. With that thought, aircraft survivability can adopt modern analytics while preserving Ball's reliable approach. Ball shows the likelihood of survivability with relation to hits on the vehicle. Other methods now take into consideration the air vehicle being exposed to hostile fire in a variety of complex encounters. Combining the two, we can simulate many scenarios encountering threats. Also, more advanced technologies can be considered to reduce the effectiveness to hostile entity exposure. Some of these methods include sensing and avoiding hostile areas, intercepting enemy with the dedicated aircraft, and swarming systems. Have a modern perspective considered, aircraft design can integrate modern aircraft survivability to generate aircraft of modern design. Together, the integration of modern methods with Ball's traditional approach can make aircraft be accurately designed to aircraft survivability in an effective and advanced way.

This chapter answers Research Question 2: Can the proposed aircraft survivability software and methods be validated and verified? The chapter presented the methods and results supporting a verified and validated survivability model. Verification and validation results were presented from error propagation and bias as well as system sensitivities analyses. With the verification and validation results, Research Question 2 can be answered as this chapter proves the proposed aircraft survivability software and methods are verified and validated. By having a verified and validated model, survivability in relation to UAV tactics and design can be further investigated and understood with confidence in the results.

6. MODEL APPLICATION EVALUATION OF UNMANNED AERIAL VEHICLE TACTICS THROUGH METRICS OF SURVIVABILITY

This chapter is about the evaluation of the UAV tactics through metrics of survivability using the developed survivability model. This chapter answers Research Question 3: What are the conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process? The contents of this chapter have been published in the *Journal of Defense Modeling and Simulation*. This chapter uses the previously developed model and the verification and validation to support the results. By applying the survivability model, UAV tactics can be effectively evaluated and understood in relevance to aircraft survivability providing improved tactical and design decision making. In this chapter, the model is applied to various tactics including the loyal wingman and fuel dumping. By using those tactics, flight performance metrics and survivability metrics are generated as results to answer Research Question 3.

Introduction

Aircraft survivability is a classical consideration of combat aircraft design and tactical development, but the fundamental model of aircraft survivability must be updated to be able to consider modern tactical scenarios that are applicable to unmanned aircraft. This dissertation seeks therefore to define the set of design tradeoffs and an evaluation of the tactical effectiveness for unmanned aircraft survivability. Traditional and modern survivability evaluation methods are presented and integrated into a computational simulation to create a probabilistic evaluation of unmanned aircraft survivability. The results demonstrate the development of design tradeoffs for a hypothetical unmanned C-130J Hercules against a single MANPADS. Discussion focuses on the demonstration of the utility of this survivability evaluation framework for consideration of survivability in UAV design, the utility of considering survivability in the design of multi-UAV configurations (including loyal wingman and swarms), and the value of the probabilistic survivability model for multi-aircraft simulations.

The unmanned aerial vehicle (UAV) has replaced the manned aircraft as the architecture of preference for a wide variety of aerial missions in research, commercial, and military applications [Garcia] [Girard]. Especially in the military application space, the UAV allows for the design of aircraft that can complete missions of lower value, higher risk profiles, and longer duration, all of which have significant impact on the concepts and metrics of aircraft survivability [Girard] [Ball]. The UAV provides an alternative to placing a human pilot in a hostile environment [Girard] [Jackman].

Aircraft survivability as a field and concept evolves from a foundation of the primacy of the pilot's life, which is self-evidently not applicable to UAVs [Ball]. Aircraft survivability methods posit a hostile encounter between an aircraft and the enemy, and seek to evaluate a metric of probabilistic survivability that can be allocated to the encounter [Jackman]. UAV survivability has been the subject of continuous research in response to the need for quantification of the threats against the aircraft, but UAV tactics have been a subject of more limited evaluation [Wang].

The fundamentals of aircraft survivability evaluation have been defined and practiced for more than forty years. By definition, where the probabilistic survivability (P_S) and the killability (P_K) of an aircraft are related as P_S = 1-(P_K), killability is the product of vulnerability (P_{vul}) and susceptibility (P_{sus}) [Ball]. The Aircraft Killability Equation is represented in Equation (1).

$$P_k = P_{sus} * P_{vul} \qquad (1)$$

These fundamentals are unchanged, but the tools available to quantify these parameters have improved with research and development. An increased emphasis on the details of the hostile encounter (quantifying the details of P_{sus}) have led to methods quantifying the details of the encounter, for example the hostile lethal envelope method.[5] An increased emphasis on the details of aircraft vulnerability (quantifying the details of P_{vul}) has led to approaches considering shot-line geometrics, a method describing the effects of hostile attacks on specific subsystems [Yang] [Sullivan].

As UAVs have grown in importance and breadth of application, survivability methods have been applied to UAVs without significant adaptation or translation [Ball]. Now, with the development and fielding of UAV-specific advanced tactics and technologies, the scope and application of survivability techniques has adapted to the need to analyze these new UA systems [Hall] [Helldin] [Humphreys]. For example, digital pheromones tactics allow a UAV to make onboard decisions to avoid or encounter a hostile entity [Sauter]. Other survivability tactics include multi-UAV system configurations [Frye] [Wang] [Biediger]. An example multi-UAV survivability tactic is "loyal wingman", where specialized UAVs are dedicated to escorting a singular aircraft [Helldin] [Humphreys]. Another multi-UAV survivability tactic is swarming, where multiple UAVs comprise a system [Frye] [Biediger]. Each advanced UAV tactic brings unique benefits to aircraft survivability, but also challenges the traditional analysis and design process for survivability, as these tactics are not directly compatible or recognizable in the Aircraft Killability Equation (1) [Helldin] [Biediger].

Based on this understanding of state of the field, there exists a need to develop simulations and evaluations of UAV survivability in the context of advanced tactics. The goal of this research effort is therefore to define the design tradeoffs and tactics that enable a deeper understanding of UAV survivability. This research presents a design study that provides this comparison among UAV survivability tactics. First, the integrated modeling and evaluation simulation for UAV survivability is presented. Then, the research tasks associated with this study apply a set of traditional survivability tactics including armoring, fuel dumping, and sprints, and a set of UAV-specific tactics including loyal wingman, swarming, and digital pheromones to a UAV survivability simulation. Results compare and quantify their differences. Discussion and conclusions concentrate on the implications of these results to the design and development of UAV systems. This research is novel in that the aircraft survivability literature does not include numerical comparison and contrasting of these particular tactics. By proposing and exercising this this adaptation of aircraft survivability methods to evaluate tactics that are primarily only applied to UAVs, we can seek to compare and contrast the costs and benefits of these novel UAV tactics within a survivability framework. These tools and examples will have utility to aircraft designers and analysts as they consider the implications of survivability on UAV design and operation.

Approach

This simulation study seeks to describe the tradeoff between UAV design characteristics, tactics, and metrics of survivability. As illustrated in Figure 38, this quantification requires the integration of models of aircraft performance, tactics, and survivability. This multidisciplinary analysis is then embedded within optimization and sensitivity analysis tools.

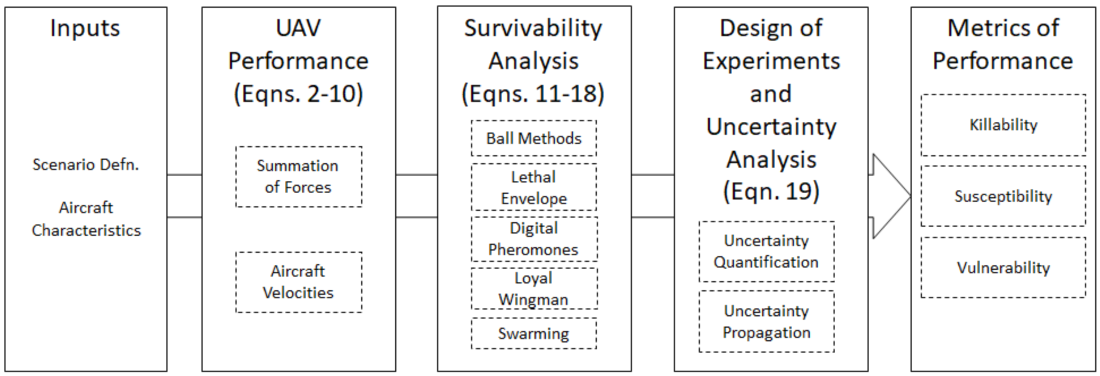

Figure 38. Optimization and sensitivity analysis operating on analysis of UAV performance, tactics and survivability

UAV Performance Modeling

The simulation of UAV performance seeks to develop a model of the performance of the UAV as a function of various design characteristics of the aircraft. This model assumes aerodynamic drag from velocity change is minor and negligible, steady level flight [Flandro]. Other assumptions include incompressible flow, standard atmosphere and gravity, as well as inviscid flow [Raymer] [Lowry] [Taylor] [Flandro].

Figure 39 describes the aerodynamics force acting on the UAV. Where L is the lift force acting on the air vehicle, perpendicular to θ_i, the angle of incidence. L is comprised of L_x , lift in the negative x direction, and L_y, lift in the positive y direction. D is the total aerodynamic drag force acting on the air vehicle. T is the total thrust acting on the air vehicle. W is the weight acting on the air vehicle.

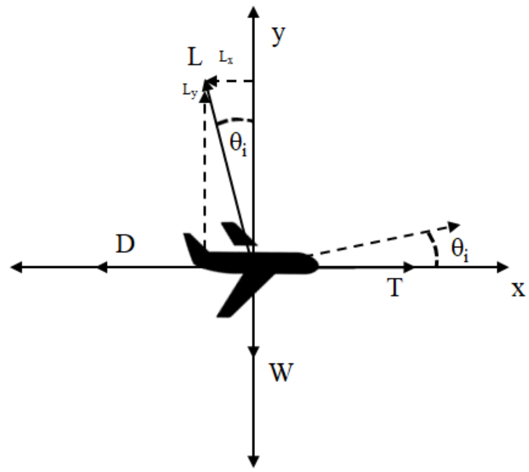

Figure 39. Aerodynamics forces diagram

Equation (2) describes the relationship of mass and gravity. Mass accelerated by g, gravity, equals a weight force, W. Under the assumption of steady-level flight, the weight force is equal to the product of the aircraft mass and the acceleration due to gravity.

$$W = m * g \qquad (2)$$

The aircraft weight force is opposed by the lifting force, decomposed into cardinal directions, L_x, L_y, as in Equation (3) and Equation (4).

$$L_x = W * \tan\theta_i \qquad (3)$$

$$L_y = L * \cos\theta_i \qquad (4)$$

Under the assumption that acceleration of the aircraft is zero, forces can be summed in the cardinal directions, as in Equation (5) and Equation (6).

$$F_x = T + D + L_x = T + D + W * \tan\theta_i = 0 \quad (5)$$

$$F_y = W + L_y = W + L * \cos\theta_i = 0 \qquad (6)$$

Equation (7) describes the summation of *x*-component velocities due to forces. Where V_x is the velocity in the *x* direction, ΔV_{ac} is the change in velocity and $V_{ac\,i}$ is the initial aircraft velocity. Equation (8) describes the summation of *y*-component velocities due to forces. No change in vertical-position due to steady level flight.

$$V_x = V_{ac\,i} + \Delta V_{ac} \qquad (7)$$

$$V_y = 0 \qquad (8)$$

Under these assumption the UAV performance simulation seeks to model various UAV tactics and their effect on UAV performance, and thereby survivability. The first tactic explored is fuel dumping, which leads to a decrease in mass, and an increase in vehicle velocity according to:

$$V_{ac\Delta} = \left(\frac{T_i}{m_{New}} - \frac{T_i}{m_{TO}} + \frac{(W_{TO} - W_{New}) * \tan\theta_i}{m_{New}}\right) * s_2 \quad (9)$$

Equation (9) describes the change in UAV velocity due to mass change. The mass-velocity equation is used to measure velocity for weight changes to the air vehicle (i.e. fuel dumping). Where, T_i is the initial thrust of the air vehicle. m_{New} is the total aircraft mass after mass change. m_{TO} is the total aircraft mass at takeoff. W_{New} is the total aircraft weight after mass change. W_{TO} is the total aircraft weight at takeoff. s_2 is the total time the aircraft is within the first half of the detection envelope and the full lethal envelope. $V_{ac\Delta}$ is the change in aircraft velocity as the aircraft leaves the lethal envelope.

The second tactic considered is velocity increasing due to temporary thrust increase (i.e. afterburners). Equation (10) describes change in UAV velocity due to a thrust change.

$$V_{ac\Delta} = \frac{(T_{New} - T_i) * s_2}{m_{ac}} \quad (10)$$

Where T_{New} is the new thrust and m_{ac} is the mass of the aircraft in which the thrust acts on.

Referencing the aircraft forces diagram, the force of aerodynamic lift is the main contributor of drag (L_x) when accounting for the mass change. The change in velocity comes from thrust acting on less mass and less lift being generated as drag (L_x) over time.

The Thrust-Velocity Equation shown as Equation (10) is used to measure velocity for thrust changes to the air vehicle (i.e. afterburners). Where T_{New} is the new thrust and m_{ac} is the mass of the aircraft in which the thrust acts on.

Execution of the aircraft performance model results in a calculation of the performance of the UAV as a function of its design characteristics and tactics. As implemented for this study, the aircraft performance output set includes its velocity, lift, and thrust.

Survivability Modeling

The inputs to the survivability model are the performance characteristics of the UAV. The aircraft survivability model then executes traditional survivability methods as well as more modern perspectives to be able to evaluate aircraft survivability using the fundamental survivability Equation (11). This model assumes clear day environmental conditions to ensure comparability to canonical aircraft flight survivability and hostile targeting literature.

$$P_s = 1 - P_k \qquad (11)$$

Aircraft survivability (P_s) is the probability of an aircraft enduring a hostile encounter [Ball]. Equation Ps=1−P_k (11) shows the Survivability Equation which is the inverse of aircraft killability, P_k, the likelihood an aircraft cannot endure a hostile encounter. Equation (11) is executed within the killability submodel shown in Figure 38.

Aircraft killability is the inverse of aircraft survivability, being the likelihood an aircraft is destroyed [Ball]. Equation (1) shows the Killability Equation which is comprised of the aircraft's inability to avoid damage, aircraft susceptibility, and the aircraft's inability to endure damage, aircraft vulnerability [Ball]. Where P_{sus} is the aircraft susceptibility and P_{vul} is the aircraft vulnerability. Equation (1) is executed within the killability submodel shown in Figure 38.

As seen in Equation (1), aircraft killability is comprised of two variables: susceptibility and vulnerability. These two metrics are highly valuable to aircraft survivability evaluations. For susceptibility, the aircraft's ability to avoid attacks is captured. For vulnerability, the aircraft's ability to withstand attacks is measured. In this chapter's results, a baseline scenario survivability is calculated. Then, aircraft susceptibility and/or vulnerability are varied through different modern tactical applications (i.e. loyal wingman, armoring, etc.). Both susceptibility and vulnerability can greatly influence aircraft survivability analysis.

For UAVs, survivability analysis requires consideration of more modern survivability considerations. In this study, we have implemented three survivability evaluation methods so that the survivability of their associated UAV tactics can be assessed. These tactics' methods are presented in the following sections.

The first of these implements a lethal envelope survivability evaluation. The model used is an aircraft survivability calculation of a one-on-one engagement incorporating lethal and detection envelopes. To generate the one-on-one engagement model (described within Figure 40 and Equation (12), the Lethal Envelope Survivability Equation) the model must define relevant scenario characteristics including aircraft characteristics (the number of hits required to on the aircraft, aircraft velocity, and more) and scenario characteristics (lethal area, reload time, and more). Figure 40 shows Equation (12) geometry of the combat scenario using nomenclature defined in Wang. With this model embedded into the simulation, aircraft survivability can be determined as a function of aircraft performance characteristics and scenario characteristics.

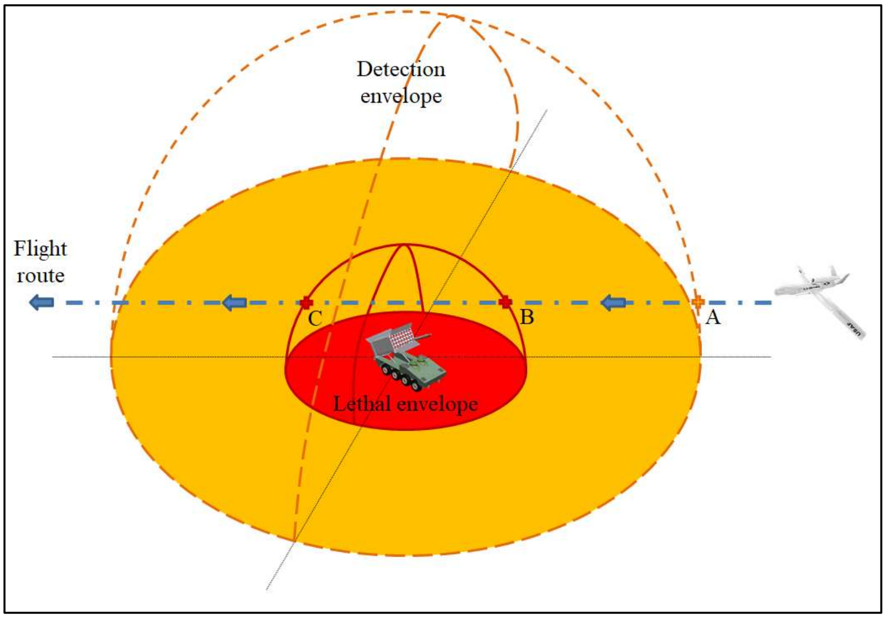

Figure 40. Lethal Envelope Scenario

Within the Lethal Envelope Survivability Equation are s_1, the time the aircraft spends within the detection envelope prior to entering the lethal envelope as the time elapse between points A and B. Variable s_2 is the time the aircraft spends within the lethal envelope as the time elapse between points B and C. Variable a is the time the hostile entity acquires the presence of the aircraft, tracks, and obtains a firing solution. The reciprocal of the mean time of detection is represented by r_d. Variable q_{SSK} is the single shot survivability. The average rate of fire is represented by r_k. Equations (12-14) are executed within the aircraft Survivability Analysis submodel of Figure 38.

$$P_s = e^{-(s_2-a)r_d} + \frac{1}{2}\sqrt{q_{SSK}}r_d e^{-r_d(s_2-a)}$$

$$\times \left[\left(1+\sqrt{q_{SSK}}\right)\frac{e^{(s_2-s_1)\beta}-1}{\beta} - \left(1-\sqrt{q_{SSK}}\right)\frac{e^{(s_2-s_1)\gamma}-1}{\gamma}\right]$$

$$+ \sqrt{q_{SSK}}\left(1-e^{-(s_1-a)r_d}\right)e^{-2r_k(s_2-s_1)}\left[sinh\left(2r_k\sqrt{q_{SSK}}(s_2-s_1)\right)\right.$$

$$\left.+ \sqrt{q_{SSK}}cosh\left(2r_k\sqrt{q_{SSK}}(s_2-s_1)\right)\right] \qquad a < s_1$$

(12)

$$\beta = r_d - 2r_k\left(1-\sqrt{q_{SSK}}\right) \qquad (13)$$

$$\gamma = r_d - 2r_k\left(1+\sqrt{q_{SSK}}\right) \qquad (14)$$

The relationship of s_1 and s_2 regarding the aircraft acceleration is described in Equation (15) as the Lethal Envelope Proportion Equation. Equations (2-16) are executed within the Survivability Analysis submodel of Figure 38.

$$P_{LE} = \left(\frac{s_1}{s_2} + \frac{1-\frac{s_1}{s_2}}{2}\right) \qquad (15)$$

P_{LE} is the proportion of the time acceleration capabilities have occurred when the aircraft is halfway through the lethal envelope. Acceleration capabilities are applied at the beginning of the detection envelope. Used to account for the average aircraft velocity within the lethal envelope, Equation (15) is executed within the Lethal Envelope submodel of Figure 38.

The new aircraft velocity equation shown in Equation (16) calculates the new aircraft velocity accounting for any changes from capabilities (i.e. fuel dumping, afterburners).

$$V_{ac\ New} = V_{ac\ i} + V_{ac\Delta} * P_{LE} \quad (16)$$

The change in velocity is the average new velocity within the lethal envelope. Where, $V_{ac\ New}$ is the new total aircraft velocity. Equation (16) is executed within the Survivability Analysis submodel of Figure 38.

The second of the survivability methods is the UAV swarm survivability method. A swarm is multiple vehicles acting as one system to complete an objective [Wang] [Biediger]. For swarming, the aircraft survivability is assumed to be measured at the swarming system level. Each swarm vehicle intercepts attacks or neutralizes hostile targets [Wang] [Biediger]. The entire system's susceptibility and vulnerability directly affect the aircraft survivability. As seen in the Swarm Survivability Equation, the swarm survivability is measured as the average survivability of each swarming air vehicle. The system survivability of a UAV swarm is described in Equation (17) as the Swarm Survivability Equation. Equation (17) is executed within the swarming and killability submodels of Figure 38.

$$P_{s\ Swarm} = \frac{P_{s1} \ldots + P_{sn}}{n} \quad (17)$$

Where $P_{s\ swarm}$ is the entire swarm survivability and n is the number of air vehicles comprising the swarm. To model the system survivability, each air vehicle's survivability is measured and then the swarm survivability is evaluated as the average air vehicle survivability.

The third survivability method considered here is the loyal wingman survivability model, where an unmanned vehicle is dedicated to protecting an escorted vehicle [Humphreys]. For loyal wingman, aircraft survivability is measured at the escorted vehicle. Loyal wingmen intercept attacks or neutralize hostile targets [Humphreys]. The loyal wingmen's susceptibilities and vulnerabilities directly affect the escorted vehicle's survivability. For loyal wingman survivability analysis, each loyal wingman intercepts hits that targeted the escorted air vehicle. In this conception, each loyal wingman's survivability is measured individually as well as the escorted vehicle. With loyal wingman, the escorted vehicle seeks to take fewer hits than it would have without loyal wingman, thereby improving survivability.

In addition to these options for tactical changes is the option to reduce the vulnerability of any of the UAVs. Some air vehicles can be single-hit-vulnerable, where other air vehicles can be multi-hit-vulnerable, with dependencies on aircraft flight conditions, munitions type, and mission. For multi-hit vehicles, our proposed survivability approach is a Monte Carlo multi-trial at large number of iterations. Within the Monte Carlo approach, for every attack from the hostile entity, the loyal wingman has an opportunity to intercept that hit, with its survival calculated based on its survivability. With this Monte Carlo approach, the loyal wingman's ability to protect the escorted air vehicle is directly related to the loyal wingman's survival. Also, a multi-hit loyal wingman or swarm vehicle's ability to deploy offensive measures is similar to the Monte Carlo survivability approach. A hostile entity can be single-hit or multi-hit vulnerable as well. Similar to multi-hit air vehicles, a multi-hit hostile entity's ability to attack will follow the Monte Carlo approach. When a hostile entity is less likely to perform additional attacks, the air vehicle susceptibility improves, due to fewer hits possibly harming the air vehicle.

Uncertainty and Design of Experiments

The analyses of UAV performance, tactics and survivability that are described in the preceding sections are embedded within a design of experiments framework. These tools allow for the evaluation of tradeoffs among the UAV design and tactical variables, allow for design studies, and for inverse design. The result is a UAV survivability evaluation model that can be used for systems engineering of UAV characteristics using survivability as a design objective.

To quantify uncertainty in this survivability model, this study uses the ISO/ANSI approach, where Type A uncertainties are estimated with sampling and Type B uncertainties are estimated without sampling [Oberkampf]. The Kline McClintock approach enables the combination of the two estimations. Without considering correlation or dependence among survivability variables, the first-order Kline-McClintock propagation of uncertainty for an equation of the form $x = f(u,v)$ is shown in Equation (18). The listed propagation of uncertainty approach is effective for simple and easily differentiable equations. For more challenging equations, the derivative can be numerically approximated or Monte Carlo utilized. In the case of type B uncertainties, the uncertainty can be estimated with the un-sampled uncertainties using the sum of the square of the standard deviation [Kline]. The Kline-McClintock equation can be expanded out to support uncertainty propagation.

$$\sigma_x^2 \cong \sigma_u^2 \left(\frac{\partial x}{\partial u}\right)^2 + \sigma_v^2 \left(\frac{\partial x}{\partial v}\right)^2 + \cdots \qquad (18)$$

Referencing Figure Figure 38. Optimization and sensitivity analysis operating on analysis of UAV performance, tactics and survivability, there are many submodels interacting with inputs and outputs. These values have uncertainty that propagate throughout the model. For instance, the aircraft velocity is an uncertain input for determining the time the aircraft spends within the detection envelope prior to entering the lethal envelope, resulting in an uncertain output. Those calculations occur within the Survivability Analysis submodel. Within the Appendix, Table 3 details the input variable and tool uncertainties of the model. This process is followed for all uncertain inputs and their related outputs throughout the model.

Results

This section provides sample results of the integrated aircraft performance and survivability modeling. The baseline scenario for evaluation of the survivability framework seeks to calculate metrics of survivability for an unmanned C130J with a single-shot killability of ~0.19 under threat from a single man-portable air defense system (MANPADS). Each scenario aircraft encounters one MANPADS attacker with a mean firing time of ~7 seconds. Under that scenario, the simulation framework presented above calculates the aircraft performance, the metrics of aircraft survivability, and the uncertainty associated with each simulation. Results for this baseline simulation are presented in Table *2*1.

Table 1. Killability results for the baseline simulations and as a function of aircraft design characteristics and tactics

	Scenario Name			
	Baseline	**High**	**Fuel**	**Armoring**

		Speed	Dumping	
Initial velocity (mph)	400	500	400	385
Final velocity (mph)	400	500	560	385
Initial weight (lbs)	155,000	155,000	155,000	165,000
Final weight (lbs)	155,000	155,000	100,000	165,000
Weight loss from fuel dumping (lbs)	0	0	55,000	0
Weight gain from armoring	0	0	0	10,000

(lbs)				
Killability $\sigma_K = 4.5\%$	**0.802**	**0.684**	**0.580**	**0.615**

As can been seen in Table 1, there are four different scenarios defined for survivability analysis. These results demonstrate that the survivability of this aircraft can be improved by changing some of the design and operational characteristics of the aircraft itself. Table 1 illustrates that this C130J in combat with a single MANPADS has a modeled killability of 0.802. If the aircraft has a higher cruise speed through the combat envelope, then the killability of the aircraft decreases, and similar effects are found for fuel dumping. Finally, armoring of the aircraft engenders a tradeoff between a decreased cruise velocity, and an improved resistance to attack. In this case, the result is an improvement in survivability, relative to the baseline.

Table 2 presents the results of the simulation in terms of metrics of aircraft survivability for a set of multi-aircraft configurations. In this case, the results of the baseline configuration are re-reported for comparison to a set of loyal wingman scenarios. The first is a scenario involving two armored loyal wingman UAVs escorting the C130J, and the second involves two unarmored loyal wingman UAVs, escorting one C-130J. The baseline scenario models a single C-130J without loyal wingman or armoring. Each scenario is exposed to one hostile MANPADS. In each case, we can compare and contrast the survivability of the C130J, illustrating that more numerous and less vulnerable loyal wingman UAVs result in reduced killability and higher survivability, relative to the baseline scenario.

Table 2. Killability results for the baseline simulations and as a function of multi-aircraft configurations

	Escorted C-130J Killability $\sigma_K = 4.5\%$
Two loyal wingmen with armor	0.377
Two loyal wingmen without armor	0.669
Baseline, No loyal wingmen, no armor	0.802

These baseline results demonstrate that the survivability model can express the changes in survivability that is due to performance changes and tactical changes for both single and multi-aircraft scenarios.

Discussion

To date, UAV survivability analyses have been based on, and are largely indistinguishable from manned vehicle survivability analyses. As the capabilities of UAV to detect attack and then tactically adapt to attack, the survivability analyses of UAVs must be able to represent the survivability effects of these tactical interventions. For this study, the results have demonstrated the ability for a lethal envelope survivability framework combined with physics-based models of the effects of these tactical interventions to model UAV survivability inclusive of these tactics. In comparing the effects of these tactics on the primary drivers of survivability, we can define the characteristics of UAV design that can lead to tradeoffs in UAV survivability evaluation.

Survivability Implications for UAV Design and Tactics

In terms of the broad interpretation of the results of this study for UAV design, there are several conventional survivability rules of thumb that emerge from the results (illustrated in Table 1 and 2). As comports with the conventional literature, UAVs with higher flight speeds, spend less time in the lethal envelope, and are consistently evaluated as having lower susceptibility and therefore higher survivability through the encounter.

Tactics that increase flight speed through the encounter, such as fuel dumping, or sprinting (through afterburners), similarly lower susceptibility and improve survivability quantitatively through this analysis. Similarly, armoring a UAV reduces its vulnerability and improves survivability. So although these gross tradeoffs may be understood in the context of conventional survivability models, the proposed simulation framework allows these characteristics to be traded off against one another through a design and tactical exploration approach.

Figure 41, Figure 42, and Figure 43 illustrate the results of these design and tactical exploration studies. In each figure, the aircraft survivability is calculated as the amalgam of killability, susceptibility, and vulnerability. These metrics of aircraft survivability are evaluated at each of the design and tactical points of consideration. For example, Figure 41 illustrates the tradeoffs that are implicit in up-armoring a UAV. Armoring improves survivability by decreasing vulnerability (the UAV is able to withstand more hits from the enemy). However, the weight from armoring also slows the aircraft (assuming constant thrust), making it exposed to more attacks due to its being in the lethal envelope for a longer duration. In an illustration and comparison of two tactics for increasing the survivability of UAVs, Figure 42 and Figure 43 compare the effectiveness of afterburning, and fuel dumping in increasing aircraft velocity, and thereby increasing survivability. In both cases, the UAV's susceptibility decreases with the effectiveness of the tactic, leading to an improvement in survivability in both cases. In Figure 43, the efficacy of each tactic is compared, showing that survivability under the fuel dumping sprint is significantly improved relative to the survivability under an afterburner sprint only tactic.

Although these results are quantitatively specific to the aircraft and enemy configurations that are described in this research, these design space exploration results illustrate the means to evaluate the tradeoff between UAV design and tactics in terms of their effect on survivability. Continued exploration of the UAV design space, and tactics would be necessary to generalize and extend these results beyond the scales, tactics, and missions considered in this study.

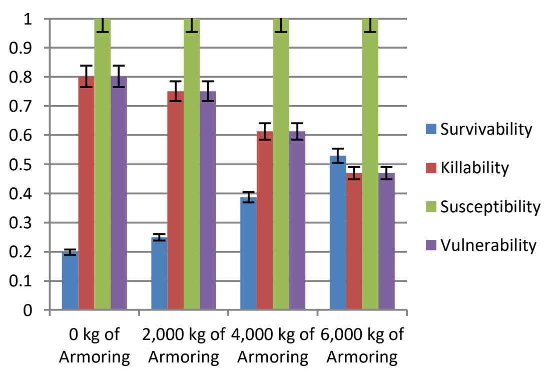

Figure 41. Armoring Effects on Survivability Metrics

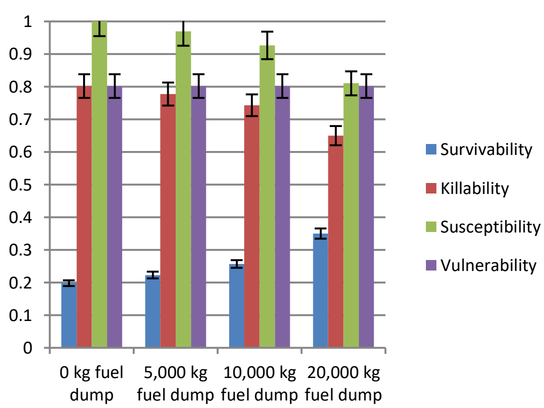

Figure 42. Fuel Dumping Effects on Survivability Metrics

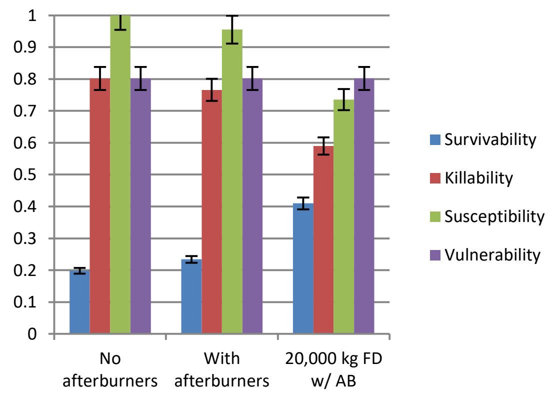

Figure 43. Afterburners Effects on Survivability Metrics

Survivability Implications for Multi-UAV Configurations

The UAV survivability evaluations that are the result of this model also carry implications for the consideration of survivability in multi-aircraft UAV configurations. Survivability is traditionally defined and evaluated for single aircraft configurations, but UAV operations and survivability tactics have often focused on multi-aircraft configurations. In this study, we can now consider the survivability implications of swarming and loyal wingman configurations for UAVs. To consider multi-aircraft survivability simulations, the probabilistic survivability of the primary aircraft is the modeled as the product of the probabilistic survivability of multiple encounters with the hostile enemy. Each loyal wingman UAV has its own survivability probability, and only when all loyal wingman UAVs are rendered ineffective, can the primary aircraft be targeted. Each metric of survivability is presented as an average of 1000 Monte Carlo trials of this procedure.

Figures 44-45 illustrate the tradeoffs among metrics of survivability for a loyal wingman UAV configuration. To note, in Figure 44, attacks are measured as whole integers as is standard in the literature when evaluating number of attacks, which is not meaningful in terms of fractional attacks. There are two tactics by which a loyal wingman UAV configuration to reduce hits on a primary aircraft, either by intercepting the hits through line of sight interference, or simply drawing attacks away from the escorted vehicle. In the example simulated here, the survivability implications of these tactics are indistinguishable. As illustrated in Figure 45, as the number of loyal wingmen increases, the susceptibility of the primary aircraft decreases, for the reason that the loyal wingman UAV is able to intercept attacks on the primary aircraft.

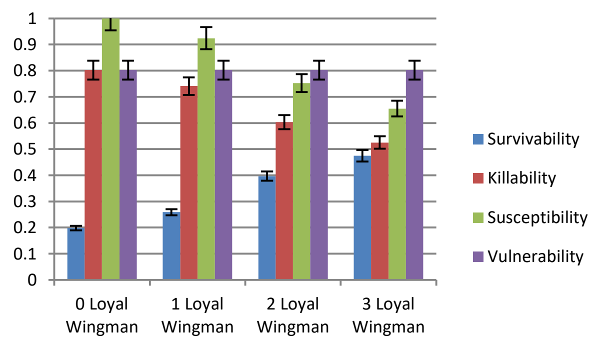

Figure 44. Loyal wingman effects on survivability metrics

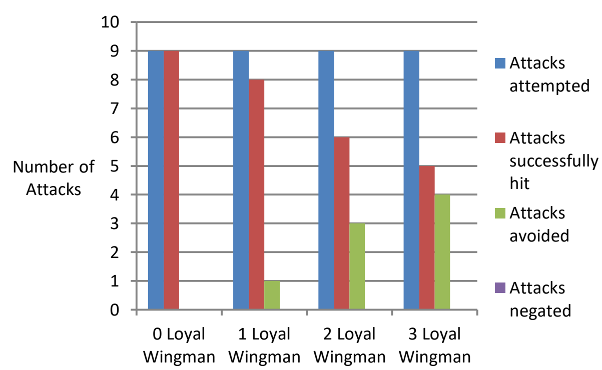

Figure 45. Integer average loyal wingman effects on attack effectiveness (n = 1000)

These results have displayed some influences multi-vehicle configuration UAVs can have in regards to survivability and its subsets including vulnerability, susceptibility, and killability.

With these new findings, more can be expanded to further understand the extent of multi-UAVs' effects on aircraft survivability.

Conclusions

This chapter has presented a method for simulation and evaluation of metrics of UAV survivability. A synthesis of survivability modeling and simulation techniques was applied to quantify the survivability costs and benefits of various tactics and approaches for UAV design and operation. The results demonstrated that survivability is affected by performance changes and tactical changes for both single and multi-UAV scenarios. The tools developed as a component of this research effort allow for the comparison of UAV design characteristics, and tactics using the metrics of survivability. A more modern perspective of aircraft survivability embraces and stimulates the further research of aircraft protection and emerging threats effects on aircraft survivability.

This chapter answers Research Question 3: What are the conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process? This chapter showed the various UAV tactics in relation to UAV survivability using the developed survivability simulation model. These tactics showed the effective UAV tactical applications to improving UAV survivability. With UAV tactics in relation to survivability understood, Research Question 3 can be answered as this chapter shows how UAVs can be used under certain conditions to which UAV designs can be improved to accommodate UAV survivability. With UAV tactics defined and related to survivability, UAVs can be designed to perform tactics that improve UAV survivability.

7. UNMANNED AERIAL VEHICLE DESIGN CONSIDERATIONS USING METRICS OF SURVIVABILITY

This chapter is about the evaluation of the design considerations of UAVs using metrics of survivability. This chapter answers Research Question 3: What are the conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process? The contents of this chapter are planned to be published in the *AIAA Journal of Aircraft*. This chapter uses the previously developed model and the verification and validation to support the results. By applying the survivability model, UAV design can be effectively evaluated and understood in relevance to aircraft survivability providing improved tactical and UAV design decision making. In this chapter, the model applies various aircraft designs by varying specific metrics of performance. By varying aircraft design parameters, UAV metrics of performance and survivability metrics are generated as results to answer Research Question 3.

Introduction

The unmanned aerial vehicle (UAV) has developed into an important component of the aviation landscape due to its ability to perform unique missions across commercial, civilian, and military applications. Whenever missions require repetitive tasks, long duration, remote operation, or high risk [Rathinam], UAVs can enable capabilities that are costly and difficult with manned aircraft. The design of UAVs and their tactics, operations, and missions requires a reconsideration of many of the fundamental metrics of performance for aircraft. For example, survivability evaluation is a rich field of study with the primary focus of analyzing and evaluating manned aircraft and their missions. As manned aircraft are replaced with UAVs in various applications in the theater of war, survivability evaluation has been forced to adapt its methods and assumptions to consider the survivability of UAVs [Rathinam]. UAVs that can be designed to maximize their effectiveness across a variety of metrics of performance, inclusive of survivability considerations, will be able to most effectively combat and compete.

Aircraft survivability methods have adapted to be able to serve the needs of evaluation of UAV designs and tactics. Whereas traditional approaches [Ball] have considered hits on target to be the primary of survivability metrics, newer approaches include more susceptibility considerations such as the time an air vehicle is exposed to attacks from a hostile [Wang], avoidance and dynamic rerouting [Sauter], stealth [Zhang], and vulnerability considerations such as armoring [Sullivan], and resiliency [Schierman]. Some researchers have developed techniques that take a vehicle-centric view of survivability. For example, Wang et al., uses the engagement range of a hostile as a lethal envelope considering the exposure the aircraft has to attacks. UAV survivability has concentrated on autonomous decision making including path planning as well as multiple-vehicle configurations such as loyal wingmen and swarming. Various UAV tactics have been proposed to improve survivability and missions' success. Other ways of influencing survivability is targetability thus improving susceptibility shown in Biediger, D., et al. by applying particular flight paths such as flocking. By reducing UAV targetability, susceptibility improves benefiting aircraft survivability. Many modern UAV applications can be leveraged to improve aircraft survivability.

This chapter presents an aircraft survivability evaluation approach that places survivability within the aircraft design tradeoff design environment. This research is novel in that it includes survivability metrics into UAV design. Whereas previous studies have considered the survivability within the context of a particular aircraft design, researchers have pointed to design of UAVs for survivability as a research challenge that requires the development of new tools and methods to address [Lunsford]. This chapter therefore presents the methods for performing survivability-integrated design of UAVs. These methods are exercised using an example UAV design study, seeking detailed design changes to the sizing and synthesis of an example UAV. Discussion focuses on the potential for realizing improvements in both conventional metrics of aircraft performance and survivability through exploration of the design tradeoffs described.

Methods

The proposed survivability-integrated UAV design process requires the development of an aircraft performance simulation that can simultaneously evaluate conventional metrics of aircraft performance and aircraft survivability. Below outlines that approach, considering the modern survivability tactics and threats affecting UAV survivability. The purpose of this research is to enable design tradeoffs between aircraft design processes and inputs and the metric of performance of survivability for UAVs. See Figure Figure *6*. Diagram illustrating project scope in the context of aircraft design and system-level design activities including mission analysis for the flow diagram of the inputs and outputs of low-level and high-level aircraft design to other -ilities. With this tool, methods, tradeoffs made explicit, this now allows mission designers to trade other -ilities against survivability in ways that are not available before. From the high level perspective the process to producing aircraft survivability is understood.

At a more detailed level, the UAV design parameters are calculated using the modern aircraft survivability analyses and simulation. Traditional aircraft performance metrics can be applied to UAVs to improve aircraft survivability in UAV design. Figure Figure *46*: Aircraft Design Related to Survivability Process Flow displays the model and simulation of Aircraft Design Related to Survivability Process Flow by capturing mission simulations that enact survivability analysis using the presented modern methods to output aircraft metrics of performance. The detailed process incorporates the application of the low-level and high-level aircraft designs. This process output can be used to develop survivability considered aircraft designs.

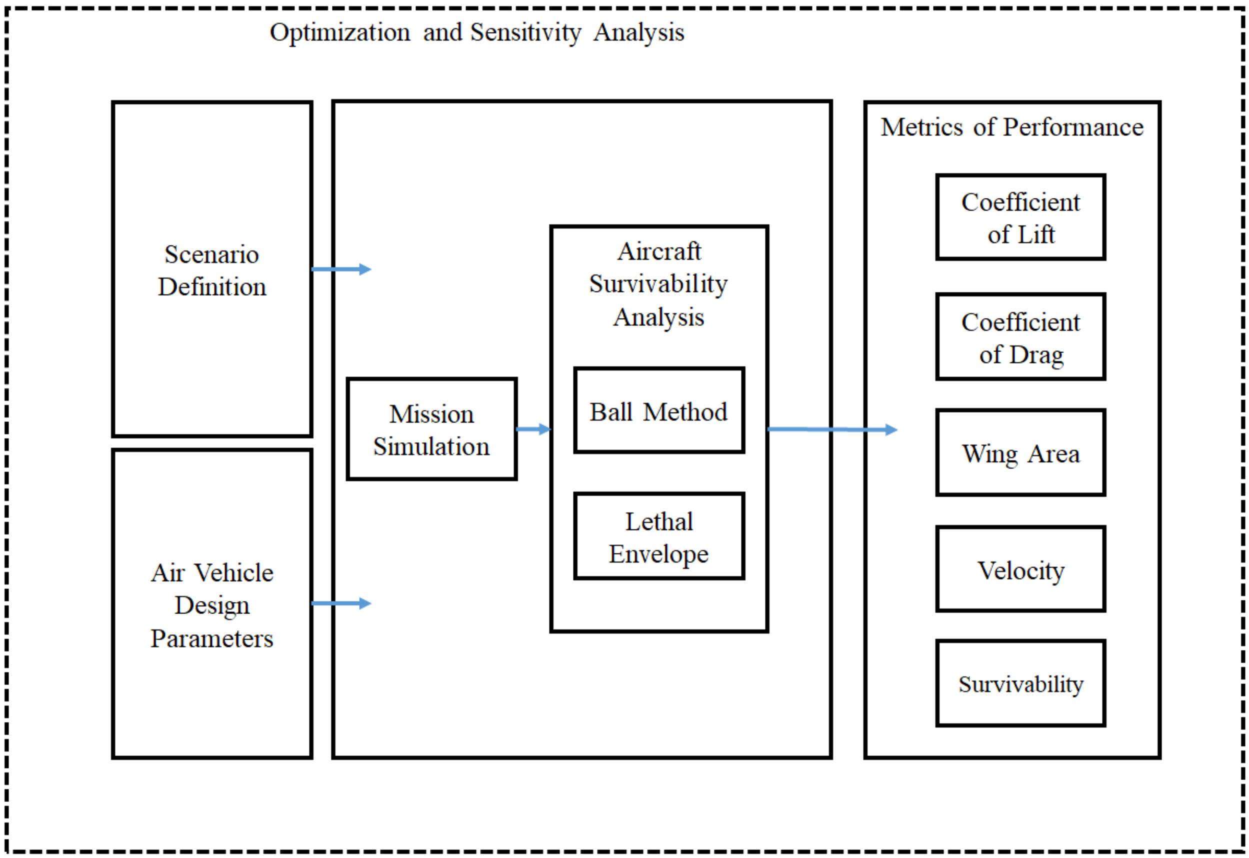

Figure 46: Aircraft Design Related to Survivability Process Flow

Aircraft Performance Modeling

All calculations for UAV metrics of performance use traditional aircraft performance methods as seen below [Raymer]. These various methods include aircraft lift and drag calculations related to velocity. As seen above, the aircraft velocity performance is related to aircraft survivability [Wang] [Ball]. These methods are applied to an MQ-9 Reaper UAV and incorporated into the UAV design. Below in Table *3* are a few default design metrics values of the MQ-9 Reaper. Note, the MQ-9 Reaper metrics of performance default design parameters are somewhat small relative to traditional and manned aircraft. This is due to the unique missions performed by the MQ-9 Reaper and other similar UAVs.

Table 3: MQ-9 Reaper Default Design Parameters

	Default design metric value
Wing Area	130 ft^2
Velocity	275 mph
Coefficient of Lift	0.6
Coefficient of Drag	0.02

Today, UAVs are often used for different missions than manned aircraft, resulting in a different design and metrics of performance. The MQ-9 Reaper is modeled as a typical modern UAV designed to perform loiter missions. MQ-9 Reapers have a long military service history and are often used in the combat theater today [Hambling]. The mission of an MQ-9 Reaper is to loiter, observe, and/ or provide air-to-ground support. To perform such missions, the MQ-9 Reaper supports sensor and munitions payloads within and outside the fuselage. Often, MQ-9 Reapers are targeted and shot down making the MQ-9 Reaper a very relative case study in regards to design changes for UAV survivability improvement.

Survivability Modeling

The survivability of the UAV is modeled using the lethal envelope [Wang] and hits on aircraft [Ball] approaches. The lethal envelope approach uses the time a UAV is exposed to hostile attacks within the lethal envelope [Wang] and hits on aircraft approach uses the number of hits on an aircraft while exposed to hostile attacks [Ball]. The relationships between the survivability modeling to the performance modeling are through the UAV metrics of performance parameter, aircraft velocity. UAV speed is related to time which is directly related to survivability due to the exposure to enemy attacks using the lethal envelope and hits on aircraft methods.

As aircraft velocity is related to survivability, aircraft velocity is also directly related to other UAV metrics of performance. These metrics include: coefficient of lift, coefficient of drag, and wing area. By specifying any of the listed parameters, the other UAV performance metrics can be calculated. With the listed relationships, aircraft survivability can be calculated for UAV metrics of performance at different values. Through the variation of UAV metrics of performance parameters, survivability in relation to aircraft design can be presented. The means of which aircraft design can be related to survivability are the UAV Metrics of Performance listed above in Figure 46.

Design of Experiments

To describe the tradeoffs and optimal solutions that can be derived from these models, the entire UAV design process is embedded within a design of experiments framework. The metrics of performance for the MQ-9 Reaper are varied, allowing for quantification and presentation of the tradeoffs that are implicit between metrics of performance and metrics of survivability. From the experiments, the indirect relationships between the metrics of performance and UAV survivability can be observed. As mentioned above, the varied performance characteristics have an indirect relationship with UAV survivability through UAV velocity.

The performed experiments vary the aircraft velocity, coefficient of lift, coefficient of drag, and wing area. Each metric of performance is observed in relation to UAV survivability and within reasonable design limits for each metric. By using modern UAV models, design constraints are considered to be relevant to the MQ-9 Reaper's current typical mission applications. With the experimentations performed, the UAV coefficient of drag and aircraft coefficient of lift can be related and presented in an aircraft survivability drag polar. The design of experiments allows for understanding of the tradeoffs to survivability for generic UAV design metrics of performance.

Results

Using the process flow shown in Figure 46, the aircraft design Metrics of Performance can be determined. Below, shows trade studies for each Metric of Performance in relationship to survivability represented as Pareto Frontiers. The represented Metrics of Performance are coefficient of lift, coefficient of drag, wing area, and velocity. These results intend to provide an understanding of each Metric of Performance in relation to aircraft survivability for inform design decision making. From the provide results, there is a large span of possible design changes. However, realistically, any design changes would be a linear change. Thus, supporting the linear system sensitivity analysis performed for verification and validation. Default MQ-9 Reaper design characteristics shown in Table 3 were used to calculate the below results in Figure 47 and Figure 48.

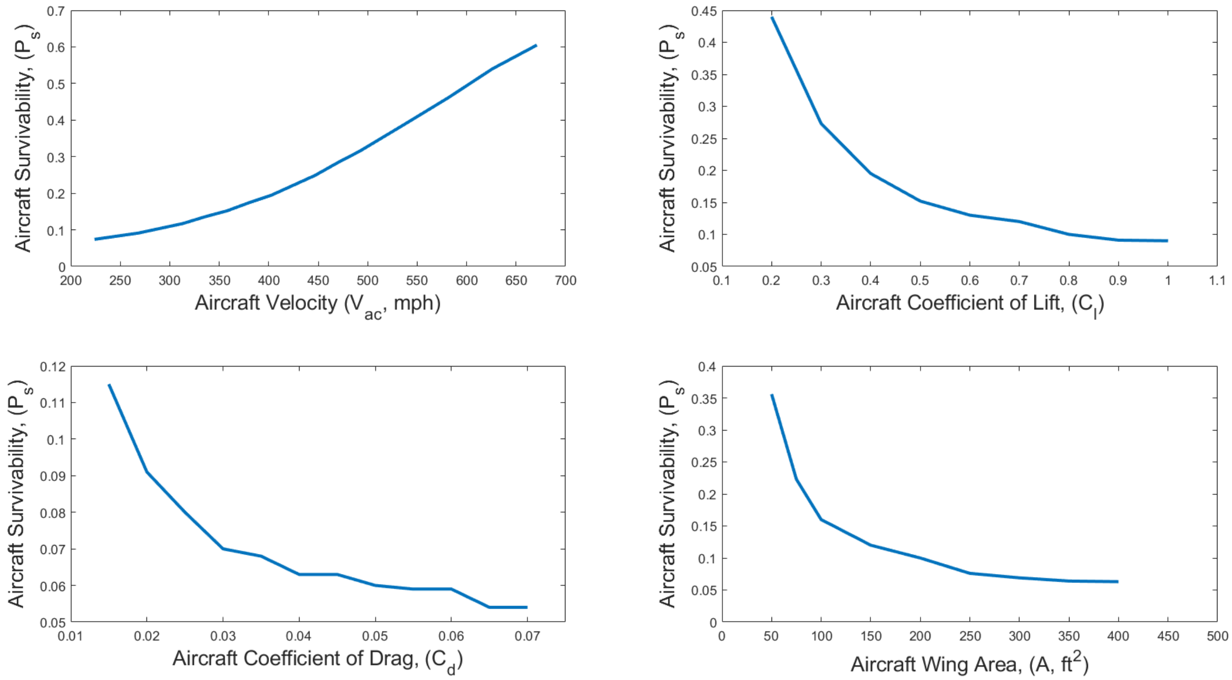

Figure 47: Aircraft Metrics of Performance vs. Aircraft Survivability (P_s) of MQ-9 Reaper

As can be seen above in Figure 47, aircraft survivability increases as coefficient of lift decreases. This is likely due to the relationship of velocity to lift described by the Aircraft Lift Equation [Raymer] shown in Equation 1. With higher lift forces, aircraft velocity decreases. A low C_L aircraft is typically is for higher velocity missions. These types are aircraft can be supersonic or hypersonic, such as a fighter. With the low C_Ls and high velocities, the fighter aircrafts are able to minimize exposure to enemy attacks, increasing survivability. In regards to the MQ-9 Reaper, a slow and high altitude loiter aircraft, a lower C_L could be difficult to apply to the design. The considerations would be to reduce the weight of the aircraft, thus reducing the required lift forces for flight. These adjustments could be in the payloads. It must be noted, there is difficultly for an aircraft to carry large weights at low C_Ls. For context, a C130J coefficient of lift is about ~0.8 and an MQ-9 Reaper coefficient of lift is about ~0.6 C_L.

$$C_L = \frac{L}{\frac{1}{2} * \rho * V^2 * A} \tag{1}$$

Also in Figure 47, aircraft survivability increases as coefficient of drag decreases. This is likely due to the relationship of velocity to drag described by the Aircraft Drag Equation [Raymer] shown in Equation 2. With higher drag forces, aircraft velocity decreases. A low C_D aircraft is typically is for higher velocity missions. Similarly to lift, these types are aircraft can be supersonic or hypersonic, such as a fighter. With the low C_Ds and high velocities, the fighter aircrafts are able to minimize exposure to enemy attacks, increasing survivability. However, fast aircraft typically have low lift as well since most drag on an aircraft is induced by lift pressure. In regards to the MQ-9 Reaper, a slow and high altitude loiter aircraft, a lower C_D could also be difficult to apply to the design. The considerations would be to reduce the high C_D surface areas of the aircraft, thus reducing the applied drag forces during flight. These adjustments could be in the payloads. For context, a C130J coefficient of lift is about ~0.04 and an MQ-9 Reaper coefficient of lift is about ~0.02 C_D.

$$C_D = \frac{D}{\frac{1}{2} * \rho * V^2 * A} \tag{2}$$

Additionally observed in Figure 47, more wing area is observed to decrease survivability. This phenomenon is likely due to the relationship of velocity to wing area as can be seen in the Aircraft Drag Equation and the Aircraft Lift Equation shown in Equation 1 and Equation 2. Low wing area aircraft again typically have high velocity missions, such as a fighter. For the MQ-9 Reaper, lower the wing area would be challenging by requiring more lift forces to sustain flight, this would counter act in some form the survivability improvement. However, by reducing the overall weight of the aircraft, the wing area could also be reduced. This is likely done by reducing the payloads' weight. For context, an MQ-9 Reaper wing area is about ~130 ft^2 A.

Figure 47 shows the relationship between aircraft velocity and aircraft survivability of an MQ-9 Reaper. As observed, by increasing the Reaper velocity, aircraft survivability increases. With a fast velocity, the MQ-9 Reaper is more likely to avoid enemy attacks due to reduce exposure duration within the lethal envelope. The increased velocity could be achieved through aircraft design by increasing the engine thrust and fuel efficiency. Thus, increasing max velocity and minimizing any additional fuel payload. Typically, aircraft with high velocities missions, for example a fighter, are able to minimize exposure to enemy attacks. Less enemy attacks result in minimizing the number of hits on aircraft, improving susceptibility and survivability. For context, an X-47b cruise speed is about ~600 mph, a C130J cruise speed is about ~400 mph, and an MQ-9 Reaper cruise speed is about ~275 mph V_{ac}.

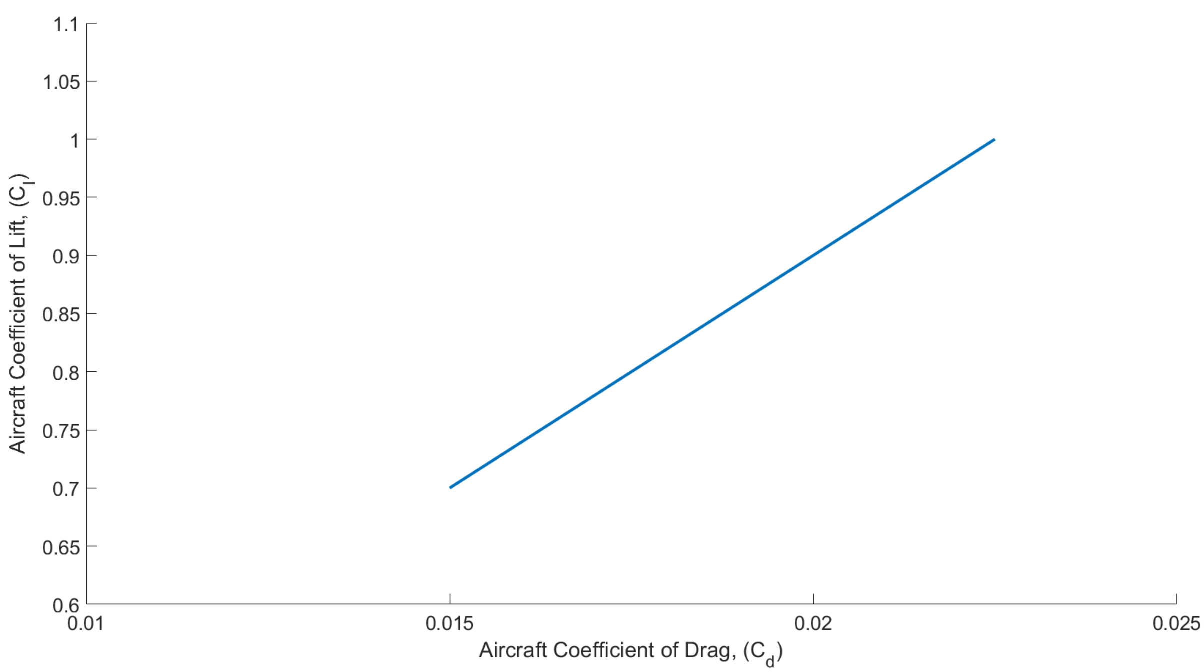

Figure 48: Drag Polar of MQ-9 Reaper

As can be seen in the Drag polar in Figure 48, as survivability decreases, both coefficients of drag and lift increase. This relationship shows the interconnectedness of the Metrics of Performance driving design decisions. By reducing the coefficient of lift, the coefficient of drag reduces as well, increasing survivability and vice versa. The Drag Polar relationship shows that in order to improve survivability, design changes must be made to reduce the coefficient of lift and the coefficient of drag. The likely design changes to reduce both coefficients are within the payloads.

Discussion

Traditionally, aircraft have been designed with the approach of measuring survivability as number of hits on a manned aircraft. As UAVs become more present in the theater, adapting survivability to more UAV-relevant considerations is important to be able to develop an aircraft design that is effective in the combat field. Today, there is an existing UAV survivability challenge as UAVs are actively engaging in combat, and are incurring combat losses. Using the approach presented in this chapter, a more detailed understanding of aircraft survivability in relation to aircraft design can be developed. With the UAV survivability analysis presented here, design choices can be traded off against survivability to enable a survivable UAV design, thereby improving UAV effectiveness in the combat field.

The results presented above illustrate the tradeoffs between survivability and various aspects of UAV performance and design. For example, the proposed analysis considers the survivability impacts of cruise velocity, allowing for aircraft survivability to be incorporated into aircraft design. Classically, aircraft survivability only considers hits on target, which is a situational approach, where no impact from changes in cruise velocity can be represented in terms of survivability. By considering the lethal envelope, the proposed models allow for aircraft survivability to be improved by increasing velocity, and thereby reducing the UAV's exposure to the lethal envelope. As observed in the results above, maximizing aircraft velocity is correlated with maximization of survivability for UAVs. Although this result is somewhat intuitive for experienced aircraft designers, many more esoteric aircraft performance metrics are demonstrated to be related to survivability including coefficient of lift, coefficient of drag, and wing area. By varying these aircraft design and performance metrics, aircraft survivability can be optimized and traded to enable the design of effective and survivable UAVs.

These takeaways can be applied to the MQ-9 Reaper as an example of how to use these results to enable an effective and survivable UAV design. The MQ-9 Reaper's mission must be considered to understand the original default design metrics. An MQ-9 Reaper provides surveillance and light air-to-ground support in a long endurance fashion as a mission. If changes to the metrics were suggested, the influence to the UAV mission must be considered. The influences in UAV design in relation to the original mission should be considered to preserve the UAV effectiveness, in theater. Each performance metric in relation to the UAV mission performance must be considered and discussed.

For the example of the MQ-9 Reaper, we can consider how to improve survivability, and thereby make tradeoffs against other metrics of performance. Decreasing the coefficient of lift is shown to improve survivability, but the UAV may only be able to support the lighter surveillance payloads or munitions payloads due to the original weight and less lift. The reward to lighter loads would mean less payloads and UAVs loss in combat. Similarly, by decreasing the coefficient of drag, survivability is improved, but the UAV may only be able to carry smaller surveillance payloads or munitions payloads to reduce the original drag. Again, the reward to smaller payloads would be less payloads and UAVs loss in combat. An obvious improvement for drag reduction is more streamlined surfaces areas, for instance airfoil and fuselages designs. This would be the simple and ideal improvement, yet drag is of minimized in aircraft design so it is an unlikely solution. For wing area, the considerations are quite different. The result of decreasing wing area would be improved survivability, but it would also make the UAV less fuel efficient directly affecting the endurance. The MQ-9 Reaper has a large wing span relative to the chord. A reduction of the chord is structurally difficult. Therefore, the wingspan might instead be shortened to reduce the wing area. Long wingspans with tapered chords reduced the wingtip vortices on the aircraft that generated negative lift. By reducing the wingspan, it is likely the UAV will need to increase the coefficient of lift to maintain the original payload. The tradeoff is less UAVs loss in combat, but a decrease in a UAV's ability to stay aloft and on station. It is likely that more UAVs could be aloft and on station if less were lost in combat. In order to decrease each of the mentioned performance metrics, it is likely the payloads would be reduced.

These design observations are gathered from the MQ-9 typical mission and the survivability results presented above. In whole, survivability for this vehicle could be improved if the MQ-9 Reaper reduced its coefficient of lift and coefficient of drag thereby reducing payloads and reducing wing area to increase velocity. The results of these design changes are of course, a tradeoff, where improved survivability leads to less effective UAVs. At present, the MQ-9 Reaper is very often lost in combat. By improving the UAV survivability, there would likely be many more MQ-9 Reapers available instead of lost in combat. With more UAVs available, the original MQ-9 Reaper mission could be performed with the survivable and available MQ-9 Reapers. It is reasonable to suggest with more survivable MQ-9 Reapers, mission cost and performance sustains and/or improves.

Conclusions

UAVs are becoming a common place aircraft in the military combat field and it is important to design UAVs to be survivable. The approach presented, adapts the traditional aircraft survivability methods to consider UAV applicable measures. Using the modern UAV survivability approach, aircraft survivability can be related to aircraft design. With the aircraft survivability to aircraft design relationships, UAVs can be designed to be more survivable. By applying the improved aircraft design, UAVs will be more effective in the combat theater. Specifically in this case study, an MQ-9 Reaper is observed to be improved in survivability with reduced aircraft metrics of performance. It is recommended to make a more survivable MQ-9 Reaper design by reducing the UAV coefficient of lift, coefficient of drag, and wing area. The result is more MQ-9 Reapers surviving combat that are less standalone effective, with more UAVs available to deploy and complete the original MQ-9 Reaper mission. With more MQ-9 Reapers surviving combat and available to support missions, mission cost is reduced and mission performance is improved.

This chapter answers Research Question 3: What are the conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process? This chapter observed varied UAV metrics of performance in related to aircraft survivability using the developed survivability simulation model. The design parameters variations showed how metrics of performance influence UAV survivability. With UAV metrics of performance in relation to survivability understood, Research Question 3 can be answered as this chapter shows how UAVs design can be designed under certain conditions to which UAV survivability can be improved. With UAV metrics of performance defined and related to survivability, UAVs can be designed to an accurate and effective survivability.

8. CONCLUSIONS

This dissertation has provided evidence to answer the three proposed research questions. A simulation framework was modeled and developed. With a simulation framework, survivability results were generated and analyzed. This dissertation intended to improve the understanding of aircraft survivability specifically in regards to UAVs. Through the research questions and results, it can be observed that aircraft survivability has been expanded and more defined. Each research question has purposed to challenge and solidify the gathered findings presented.

Research Question 1 intended to propose the feasibility of modeling and simulation aircraft survivability for results generation. This question was seen as answer since aircraft survivability was simulated and results were created. The simulation framework leveraged robust aircraft survivability methods such as hits on target and the lethal envelope, solidifying the answering of Research Question 1. With a simulation framework created, the other research questions had a testbed to pursue their questions.

Research Question 2 intended to ensure the reliability of the results generated from Research Question 1. By having the results verified and validated, understandings created in this dissertation could be understood as true. The means of the verification and validation process used reliable methods including a system sensitivity analysis with Kline-McClintock sensitivity and Monte Carlo iterations. Results could now be presented with sensitivities for a better understanding of the accuracy of the provided results. By having Research Question 2 answered, the simulation framework was deemed reliable and capable to support answering Research Question 3.

The intent of Research Question 3 was to define the relationship of aircraft survivability into the aircraft design process. Using the simulation framework developed from Research Question 1, aircraft survivability was simulated with various tactics and metrics of performance. These tactics included fuel dumping and armoring to show the relationship of tactics to aircraft survivability. Also, the metrics of performance were measured in relation to aircraft survivability to improve the design process. With aircraft survivability in relation to design better defined, aircraft could be designed to be more survivable.

Each research question provided an answer to the capabilities of measuring aircraft survivability. By having a simulation framework, aircraft survivability could be gathered for various UAV designs encountering hostile attacks. With a verified and validated framework, the measurements produced from the framework can be relied upon and better understood. Lastly, an integrated tactical and performance methodology with the framework enables an aircraft design to be related to aircraft survivability. The combination of the three proposed research questions has reliable aircraft survivability understanding, measurement, and application to aircraft design.

Research Contributions

The research contributions of this dissertation effort include:

1) A computational tool for UAS group sizing and synthesis that allows for the evaluation of aircraft survivability in tradeoff with aircraft performance metrics
2) The comparison of modern UAS communication and coordination tactics using metrics of aircraft survivability
3) A rigorous verification and validation based uncertainty estimation for aircraft survivability modeling

4) A comparison of aircraft-survivability realized UAS design to designs utilizing traditional naïve methods of aircraft survivability

Publications list including both the journal and conference publication.

1) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Review,” NDIA Aircraft Survivability Symposium, 2018
2) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Framework,” SCS Spring Sim, 2019 (Proceedings additionally published in IEEE)
3) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Framework,” NAFEMS MBSE Conference, 2019
4) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Framework,” NDIA Aircraft Survivability Symposium, 2019 (Abstract accepted, declined presentation)
5) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Modeling Evaluation and Optimization for Multi-UAV Operational Scenarios,” AIAA SciTech 2020
6) Lunsford, I., and Bradley, T.H., “Aircraft Survivability Modeling for Multi-UAV Operational Scenarios and Emerging Threats,” SCS Summer Sim ‘20, 2020
7) Lunsford, I., and Bradley, T.H., “Evaluation of Unmanned Aerial Vehicle Tactics through Metrics of Survivability,” SCS Journal of Defense Modeling and Simulation, 2021
8) Lunsford, I., and Bradley, T.H., “Simulation of the Effect of UAS Tactics on UAS Survivability Metrics of Performance,” AIAA Rocky Mountain Annual Technical Symposium, 2021
9) Lunsford, I., and Bradley, T.H., “Optimized Swarming UAS design for Aircraft Survivability,” AIAA Journal of Aircraft, 2021 (planned)

Future Work

This research effort sets up numerous possibilities for future work investigating aircraft survivability, UAVs, and the war theater. Since it has been established that the presented evaluation methods, tactics, and scenario conditions can be measured as influencing survivability, more possibilities to elucidating those influences can be investigated. For instance, the system level approach has been observed as effective, yet could be combined with component survivability analytics. In addition, this research presented a set of various conditions a UAV can encounter in the war theater. There are more conditions that would be beneficial to observe. Not only can the scenarios be expanded upon, but UAV autonomous capabilities can be used to affect survivability including flight-path planning. Lastly, another area of expansion would be aircraft survivability effects on mission effectiveness.

Aircraft survivability is a complex metric of performance requiring many situational factors to be considered. This dissertation research has focused on aircraft survivability at the system-level. Today, there are many forms of measuring aircraft survivability including component-level methods such as shot-line geometrics. A worthy pursuit of investigation would be integrating component-level methods with the system-level methods presented. This approach would likely require detailed aircraft system and component understanding as well as a strong computational machine to process the simulations. By using component-level with system-level aircraft survivability, the fidelity of the presented results could be more certain.

In regards to scenario conditions, there are many interesting situations that should be observed. Some of these are aircraft offensive capabilities including munitions payloads or electronic jamming. These capabilities may eliminate an enemy threat and improve survivability. Another possibility is defensive capabilities including stealth and maneuverability. These capabilities may enable a UAV to mitigate enemy effectiveness. Lastly, enemy effectiveness could be expanded upon to better understand how robust aircraft survivability is. All of these scenario conditions could be investigated to provide a more detailed understanding of aircraft survivability.

Another unique capability with UAVs is the autonomy of decision making. UAVs can be equipped with onboard sensors and processing that could enable them to automatically improve survivability. Some proposed methods existing include real-time flight path planning. These methods leverage approaches including digital pheromones. There seems to be a possibility of improving aircraft survivability by automatically avoiding hostile encounters. Applying digital pheromones simulations could show the effectiveness of real-time flight path planning for UAV survivability.

Lastly, UAV survivability is observed to understanding a UAV's ability to endure hostile encounters. A next step to understanding survivability importance is relating UAV survivability to mission effectiveness. Theater level simulations in conjunction with UAVs could provide insight as to the importance of UAV survivability for mission success. Entities in the simulation could include common friendlies and hostiles such as tanks, troops, and ships. By expanding the simulation to a theater level, UAV survivability may be measured with that of mission effectiveness. Such scenarios would likely require entity capabilities understanding as well as a strong computational machine to process the simulations.

This research has provided a solid base for many efforts to expand aircraft survivability in relation to UAVs. The methods and conditions presented have shown that aircraft survivability is measurable and understood with a system understanding. All future work can use the system understanding established to add more features with additional detail. Aircraft survivability is an important metric, any efforts invested to the future expansion of this research is to benefit a widely regarded aircraft metric. By using the presented methods, the future work can be of great benefit and contributions to the understanding of aircraft survivability.

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APPENDIX

Survivability Example Calculation:

$P_k = 0.8$

$$P_s = 1 - 0.8 = 0.2$$

Killability Example Calculation:

$P_{sus} = 0.85$, $P_{vul} = 0.8$

$$P_k = 0.85 * 0.8 = 0.68$$

Mass-Velocity Change 15,000 kg Fuel Dump Example Calculation:

$T_i = 131{,}880\ N,\ m_{TO} = 70{,}305\ kg,\ m_{New} = 55{,}305\ kg,\ W_{TO} = 155{,}000\ lbs,$

$W_{New} = 121{,}950\ lbs$, $\theta_i = 3.0°,\ s_2 = 55.6\ sec$

$$V_{ac\Delta} = \left(\frac{131{,}880\ N}{55{,}305\ kg} - \frac{131{,}880\ N}{70{,}305\ kg} + \frac{(155{,}000\ lbs - 121{,}950\ lbs) * \tan 3.0°}{55{,}305\ kg}\right) * 55.6\ sec$$

$$\approx 0.04\ km/s$$

Thrust-Velocity Change Afterburners Example Calculation:

$T_i = 131{,}880\ N, T_{New} = 151{,}665\ N,\ m_{ac} = 70{,}305\ kg,\ s_2 = 55.6\ sec$

$$V_{ac\Delta} = \frac{(131{,}880\ N - 151{,}665\ N) * 55.6\ sec}{70{,}305\ kg} \approx 0.02\ km/s$$

Lethal Envelope Proportion Example Calculation:

$s_1 = 50.0\ sec, s_2 = 55.6\ sec$

$$P_{LE} = \left(\frac{50.0\ sec}{55.6\ sec} + \frac{1 - \frac{50.0\ sec}{55.6\ sec}}{2}\right) \approx 0.95$$

New Velocity Example Calculation:

$V_{ac\,i} = 0.18\ km/s, V_{ac\Delta} = 0.04\ km/s, P_{LE} = 0.95$

$$V_{ac\,New} = 0.18\ km/s + 0.04\ km/s * 0.95 \approx 0.22\ km/s$$

Table 4. Design and CA Variance Errors

Inputs	Outputs	Design variable fractional error	Output fractional error
Aircraft velocity	s1	0.5	0.1
Aircraft velocity	s2	0.5	0.1
Aircraft velocity	Hostile firing rate	0.5	0.1
Hits on aircraft, hostile firing rate, s1, s2,	Aircraft killability	0.5	0.2

The design variables and output errors can be seen in Table Table *4*. Design and CA Variance Errorsas minimal.

<u>Defense of the use of an assumption of local linearity for System Sensitivity Analysis:</u>

Systems Sensitivity Analysis is used in this research to perform validation activities. Specifically, SSA allows for quantifying the output uncertainty due to expected ranges of input uncertainty. SSA relies on an assumption of local linearity, and the validity of this assumption can be assessed by:

- Comparison of slopes at two relevant design points. This test reveals that there is <15% difference in slope between the Original Reaper design point, and the improved survivability Reaper design point. Slopes are indicated in Figure Figure *49*. Demonstration of local linearity in the aircraft design space.

- No discontinuities present in the design space.
- This area of the design space is assumed to be locally linear, but non-linearities exist beyond the relevant design space.

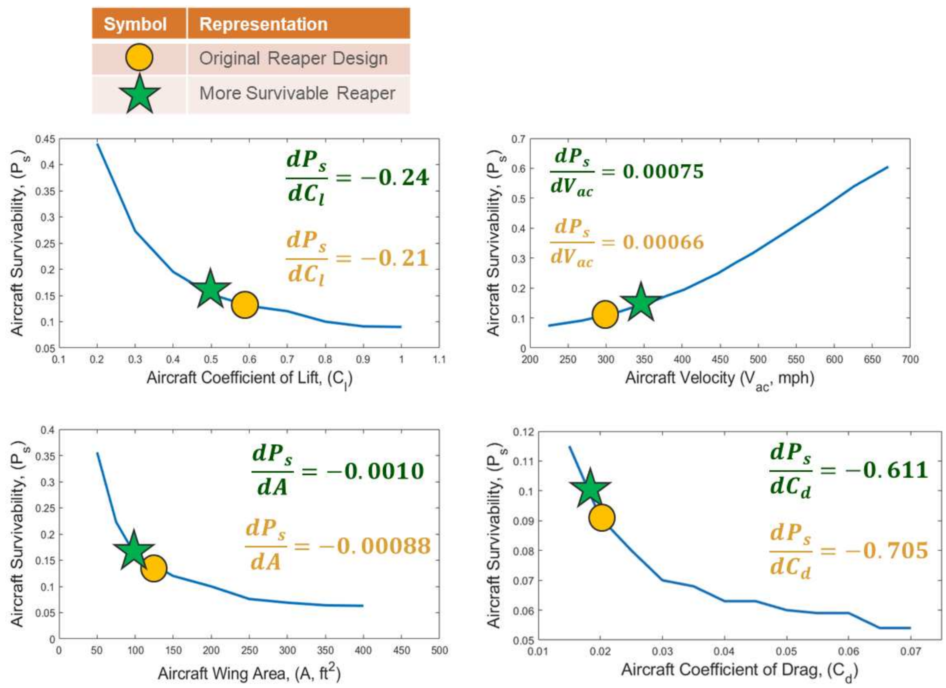

Figure 49. Demonstration of local linearity in the aircraft design space

To ensure the effectiveness of these suggested design changes, linearity should be preserved to ensure validity. By selecting design parameters within the linear design space, the validity of the UAV applications is preserved. A systems sensitivity analysis is used in this research to perform validation by quantifying the output uncertainty due to expected ranges of input uncertainty. As can be seen in Figure Figure *49*. Demonstration of local linearity in the aircraft design space, any practical design changes would be within the linear and valid design space.

LIST OF ABBREVIATIONS

ACS: Aircraft Combat Survivability

AIAA: American Institute of Aeronautics and Astronautics

AIM: Air Intercept Missile

AirSurF: Aircraft Survivability Framework

ANSI: American National Standards Institute

AS: Aircraft Survivability

CA: Contributing Analyses

CDF: Cumulative Distribution Function

CI: Confidence Interval

DP: Digital Pheromone

DSM: Design System Matrix

ISO: International Standards Organization

LSV: Local Sensitivity Vector

LW: Loyal Wingman

MANPADS: Man-Portable Air-Defense System

MDA: Multidisciplinary Analysis

MDAO: Multidisciplinary Design, Analysis, and Optimization

MDO: Multidisciplinary Design and Optimization

RIM: Radar Intercept Missile

UAV: Unmanned Aerial Vehicle

UI: User Interface