AIRCRAFT SURVIVABILITY MODELING FOR MULTI-UAV OPERATIONAL SCENARIOS AND EMERGING THREATS

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ABSTRACT

This project presents modern aircraft survivability scenarios with emphasis on multi-UAV operations. Traditional and modern approaches are analyzed to present strengths and gaps of current aircraft survivability analysis. Newer approaches of aircraft survivability are presented alongside traditional approaches. The presented approach is applied to a simple aircraft survivability scenario of a C-130J Hercules against a single MANPADS with modeling and simulation. Monte Carlo analysis applied to the scenario to determine survivability and sensitivity. Error propagation is discussed as an existing tool. A MDAO approach is discussed to incorporate aircraft design with the produced aircraft survivability results as a potential improvement to the analysis. In whole, the project provides analytics of a modern perspective on aircraft survivability amongst the reality of emerging threats and considers proposing improvements the overall aircraft design process.

Keywords: survivability, sensitivity, design, aerospace, MDAO.

1 INTRODUCTION

The focus of this project is the modeling, design, and operation of unmanned aerial vehicles with an emphasis on evaluation and optimization towards metrics of aircraft survivability. Here, the unique and modern operational scenarios will be described along with the high-level considerations for emerging threats. Also, the motivational background to the topics of modeling and simulation, aircraft survivability, and aerospace engineering are described. Modeling and simulation is widely used throughout the aerospace community for design decision support regarding tradeoffs among performance, cost, and aircraft survivability. Aircraft survivability is measured to define the capability of an aircraft to survive an encounter with an enemy, as well as being an important metric for combat mission analysis. With the of 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 intends to design and manufacture aircraft with high survivability to provide to their customers. The motivation to analyze aircraft survivability with modeling and simulation came in an effort to support the warfighter in an effective manner. In whole, the aircraft survivability modeling simulation presented approaches intends to provide more useful metrics for practical combat scenario applications.

2 OVERVIEW

2.1 Modeling Approach

A model represents behavior, structure, or information, and can be virtual or physical. Models often have inputs and outputs, and utility in describing physical phenomenon (Borky, 2018) (Ziegler, 2000). A simulation is a represents a model within a time-based sequence to, often represented by states (Loper, 2015) (Ziegler, 2000). By abstractly represent a phenomena though modeling and simulation, insight can be provided into the realistic capabilities of the aircraft. Modeling provides the opportunity to measure the system effectiveness using verified and validated approaches. This project 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 fit for purpose. Verification is the activity of reasonably arguing a model's proper implementation with respect to the model description and solution (Moffat, 1997) (Stolfi, 1997). Typically, verification references established theories and seeks to comparing measurements of the model to established theories while describing explanations (Oberkampf, 2010). For instance, a model of turbulent flow could be verified through comparison to established theories suggesting that phenomena (Selig, 2004) (Somers, 1981). Validation is the activity of deterministically arguing the amount of accuracy in a model representing the physical world under the intended uses (Moffat, 1997) (Stolfi, 1997). Validation often uses measured information from the model to provide an argument for agreement between experimental evidence and modeling and simulation metrics (Sargent, 2018). 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, 1997) (Selig, 2004) (Somers, 1981). Metrics of validation can include modeling uncertainty, pure error estimate, and experimental error (Kline, 1953) (Moffitt, 2007). Validation often relies on verification for support (Sobieszczanki, 1988). The presented approaches were simulated with robust verification and validation metrics and approaches. These metrics and physical comparables are typical accepted verification and validation evidence in the modeling and simulation community. This approach uses common verification and validation methods to demonstrate predictive to and convince the modeling and simulation community of findings.

2.2 Aircraft Survivability with Scenarios

The term "aircraft combat survivability" (ACS) 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, 2003). Aircraft combat survivability is one of the most important metrics of aircraft performance and design (Hall, 2009). 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, 2003). 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, 2003). Also, susceptibility is the aircraft's inability to avoid hostile attacks (Ball, 2003). Lastly, vulnerability is the aircraft's inability to withstand hostile attacks (Ball, 2003). Each metric effects the survivability metric. An understanding of aircraft survivability has been demonstrated to have considerable impact on military tactics and strategic decision making in combat (Helldin, 2012).

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, 2003). 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, 2009). 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, 2003) (Jun, 2013) (Yang, 2009). Many of the design tools that are available today implement Ball-type and shot-line methods, including BRAWLER, AFSIM, etc. (Hall, 2009) (Noh, 2007). The presented methods are not sourced from any proprietary or restricted tools. All the tools surveyed in this section are highly proprietary and typically require specific reasoning and/or clearance to acquire.

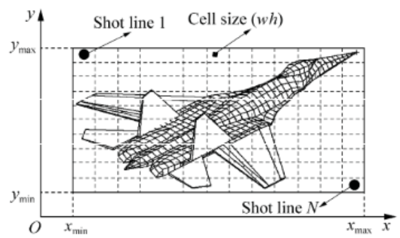

Figure 1: Traditional Shot-line Geometric Approach (Yang, 2009)

For the shot-line geometrics approach, attacks effectiveness on the air vehicle are 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, 2006). Measuring shot-line geometrics is effective for aircraft design scenarios, yet somewhat unpredictable in a mission level engagement. For this project, shot-line geometrics is recognized as specific attacks at a subsystem level to system level. In result, shot-line geometrics become out of scope due to the focus of this survivability approach is system level to mission level. With an expanded scope being from subsystem to mission, a robust, yet computationally expensive analysis could be developed. In order for the simulation to be effectiveness, highly precise threat effectiveness would be provided to an extent of highly specific and predictive understanding. Instead of shot-line geometrics, other higher level and generic methods are used.

The literary reviews discovered the state of being for aircraft survivability and an opportunity for a modeling and simulation application. As the research progressed, Ball's method was seen as prominent and appropriate for almost every application. Shot-line geometrics were also discovered as effective and useful detailed aircraft survivability approaches, specifically for subsystems. In this project, the system level application suggests the shot-line geometrics as out of scope. 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 require 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, 2017) (Sauter, 2005). These in whole have been the basis of the aircraft survivability improvement approach.

Relative to these traditional aircraft survivability (AS) methods, new AS performance metrics and AS concepts have been developed to keep pace with emerging aircraft tactics and technologies (Broadston, 2000). 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, 2003). 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, 2016) (Erlandsson, 2013) (Schaffer, 1993). The modern threats today include MANPADS, AIMs, RIMS, etc. where the traditional threats have been flak, small arms, etc. (Clothier, 2018). To ensure survivability is accurate, emerging threats are being measured against modern countermeasures. The newer modern methods discovered take into account more advanced ways to improve aircraft survivability.

The newer survivability methods are similar in nature 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, 2009). 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, 2013). 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, 2013). 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. By measuring distance and entity capability, lethal envelope introduces enemy effectiveness beyond the traditional approaches. 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 and implemented. The approaches intend to bring improvements to survivability analysis while measuring the traditional approaches as supplemental perspective. For example, the digital pheromone approach, described in Figure 3, seeks to sense and avoid hostile areas (Frye, 2019) (Sauter, 2005) (Teo, 2013). The loyal wingman approach, shown in Figure 4, seeks to intercept enemy fire and reduce hits on the aircraft (Humphreys, 2016) (Humphreys, 2015). Swarm approaches, illustrated in Figure 5, considers aircraft survivability as a system rather than one vehicle (Wang, 2019). All the listed scenarios are unique with specific considerations towards survivability. Each of these methods is a step toward a more modern and relevant aircraft survivability analysis.

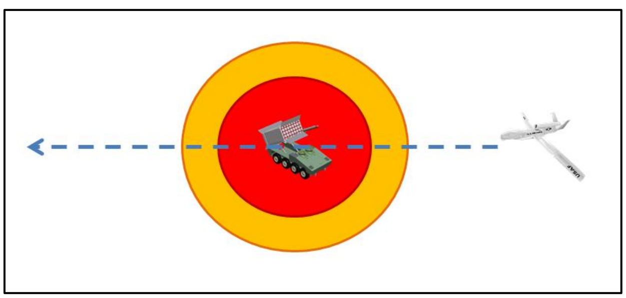

Figure 2: Simple Lethal Envelope Scenario (Wang, 2009)

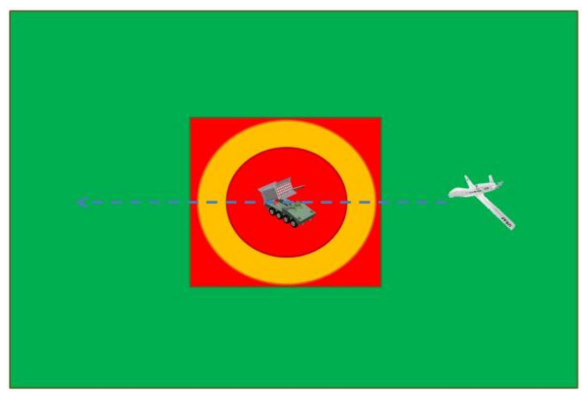

Figure 3: Digital Pheromone Approach (Sauter, 2005)

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, 2011). 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, 2017) (Erlandsson, 2014). For aircraft survivability, digital pheromones plays the role of locating potential hostile areas and deciding how best to avoid (Jia, 2016). 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, 2014). 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 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. An autonomous, threat detecting vehicle brings about a likely effective avoidance approach to survivability. Rather than eliminating or enduring a threat, all around avoiding the encounter improves the survivability in whole. The vehicle will often avoid hostile areas unless there is no other navigation option (Zhou, 2017). By avoiding enemy hostile areas, the vehicle can reduce the amount of hits it will receive, improving survivability.

Loyal wingmen are dedicated air vehicles to protecting an escort vehicle either offensively and/or defensively (Humphreys, 2017). Figure 4 shows a loyal wingman scenario where multiple vehicles are escorting an air vehicle in the middle. 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 to intercepting hostile entity attacks as well as neutralizing hostile entity threats (Sonawane, 2011). 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, 2015). Each consideration is investigated with these 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 will be likely option to simulate with. As threats advanced, offensive capabilities can expand. Measuring the loyal wingman with various offensive capabilities likely varies the effectiveness of loyal wingmen's offesnes.

Currently, instances of the loyal wingman include Boeing developing loyal wingman UAV from Royal Australian Air Force. The vehicle is described as four to six vehicles operating in conjunction to an escorted vehicle with performance similar to a fighter with sensor applications to conduct reconnaissance, surveillance, intelligence, and electronic warfare. A loyal wingman could 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, 2007). Where, an instance of offensive electronic warfare could be disabling an anti-air ground installation with directed energy. Loyal wingmen seem to be an effective measure of defending an air vehicle. An additional offensive or defensive capability has the opportunity to reduce the number of hits of the escorted air vehicle or preventing an enemy entity from launching an attack. Each capability could be invaluable for supporting an escort vehicle (Humphreys, 2016).

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. Today, swarms are feasibly effective means to accomplishing specific missions. With numbers, swarms are seen to be capable of completing missions with acceptable losses of air vehicles. In that perspective, the survivability is viewed as system level, rather than individually measured per vehicle. Utilizing swarms to attack enemy entities can vary from ranged targeting to vehicles delivering their equipped payloads with onboard system navigation. Collectively, a swarm is a mission centric approach with a likely high-survivability due to the number of targets within the system.

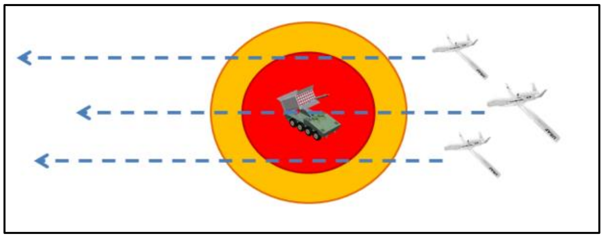

Figure 4: Loyal Wingman Approach (Humphreys, 2016)

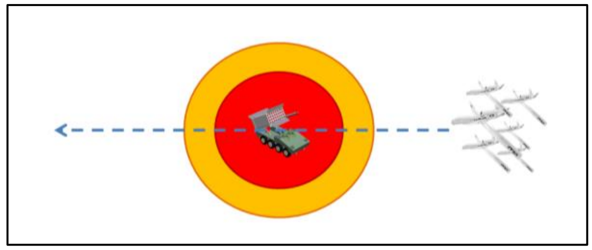

Figure 5: Swarm Approach (Sauter, 2005)

The applications can be expanded to incorporate strengths of each approach. Each approach has benefits to survivability, by combining approaches, more robustness may be achieved. On consideration would be incorporating loyal wingman with digital pheromones. Not only would the escorted vehicle be defended, the vehicle would also be avoiding any conflicts intentionally. See Figure 6 for a depiction of the blended digital pheromones loyal wingman scenario. See Figure 7 for a depiction of the blended digital pheromones swarm scenario. These blends of approaches can be applied to many other survivability scenarios. The important value is modern threats and countermeasures make survivability a dynamic metric. Having modern survivability measured with traditional survivability, provides opportunity to improve the accuracy of the metric with the development of emerging threats.

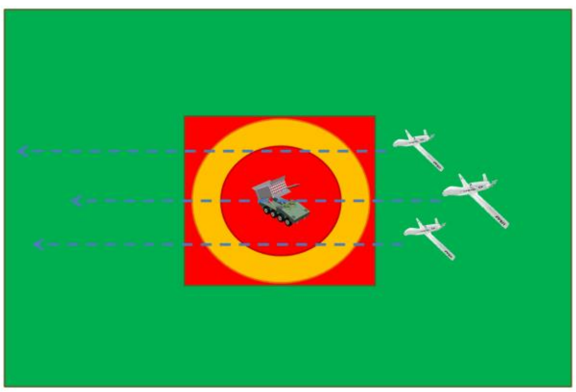

Figure 6: Digital Pheromones Loyal Wingman Approach (Wang, 2009) (Humphreys, 2016)

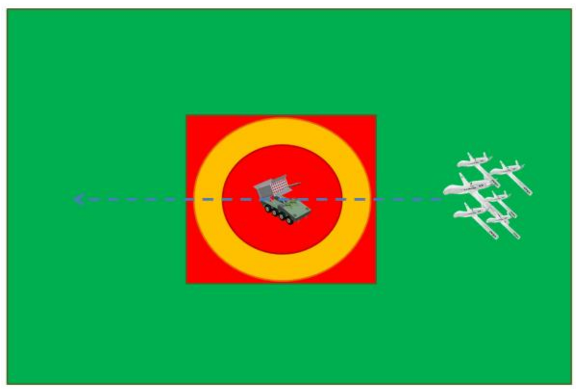

Figure 7: Digital Pheromones Swarm Approach (Wang, 2009) (Sauter, 2005)

2.3 Summary

Based on these observations, there exists a considerable gap in the understanding of the broader design space around the design of UAS for survivability. By identifying a few modern approaches, aircraft survivability analysis can be meaningfully supplemented. 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. By incorporating modern scenarios, analyses, and approaches, aircraft survivability can build towards stronger accuracy. This effort will seek to advance the state of knowledge in this field by addressing these gaps.

3 MODELING APPROACH

3.1 Overview

The current aircraft survivability approach is driven to model hits on target and location of hit analysis (shot-line geometrics) (Ball, 2003) (Magister, 2010) (Yang, 2009). The approach defined in this research seeks to provide more considerations to various important aircraft survivability factors. This approach considers the time within engagement range of an enemy entity (lethal envelope) (Erlandsson, 2013) (Wang, 2009). Also, various other advanced capabilities to engage with emerging threats have been applied. These considerations are digital pheromones, loyal wingman, and swarming (Frye, 2019) (Humphreys, 2016) (Wang, 2019). Each advanced scenario provides an opportunity to expand upon the traditional methods of aircraft survivability. All the combined analytic considerations have a more robust and realistic understanding of aircraft survivability while preserving the value of traditional aircraft survivability approaches.

3.2 Aircraft Survivability Modeling with Respect to UAVs

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, 2003) (Humphreys, 2016) (Wang, 2019). 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, particularly Kline-McClintock (Kline 1953). Sensitivity analysis to identify aircraft design parameters closely related to aircraft survivability has been used in conjunction with Monte Carlo applications and multi-disciplinary analysis and optimization (MDAO). The new aircraft survivability approach with the old in relation to aircraft design has been compared and contrasted.

3.3 Scenario Tactics

The AS community has stated their preference to be able to consider the modeling of AS in early design stages of a UAV/UAS design process (Berg, 1997). Design considerations for UAS are modeled in a framework that allows for representation of the identified modern aircraft survivability tactics and scenarios. Tactics and performance of modern UAS are represented parametrically in an integrated and optimizable system model of aircraft survivability. There are a number of challenges that are associated with executing this representation. 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. A baseline aircraft survivability framework and toolkit has been created. Open-Source implementation for AS community and military users has been created. The intent is to analyze modern survivability scenarios while enabling others to use the framework genertated for analysis. Also, modern UAS-relevant tactics and performance models (Digital Pheromone method, Loyal Wingman, Swarm) has been implemented (Ball, 2003) (Humphreys, 2016) (Wang, 2019).

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. Aircraft design process incorporation is one of the more valuable products of the modern survivability analysis.

3.4 Verification and Validation

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 seeks to understand the level of validation and verification that can be achieved using the models proposed. With Monte Carlo, CDFs and inverses with errors are generated. From the Monte Carlo analysis, the fitted number of hits histogram can be seen within Figure 8. From observation of the CDFs and Kline-McClintock analysis, sensitivities are observed. Some of the observed sensitivities are shown within Figure 9. As can be seen, aircraft killability (Pk) has the most sensitivity to the time within a lethal envelope (s2). Onward, MDA is incorporated to gain more detail regarding survivability generation with bias error. The proposed aircraft survivability software and methods are validated and verified.

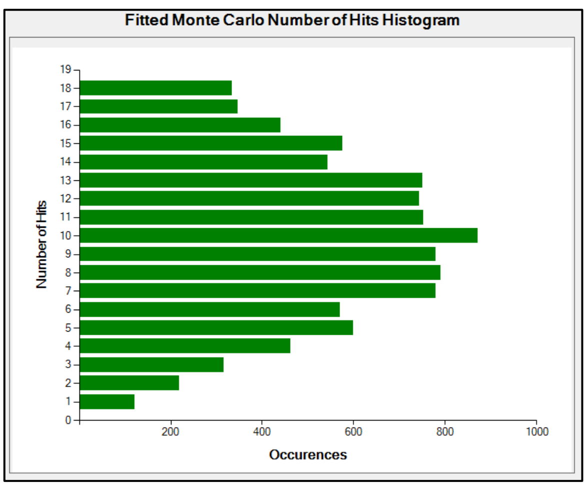

Figure 8: Monte Carlo Number of Hits Histogram

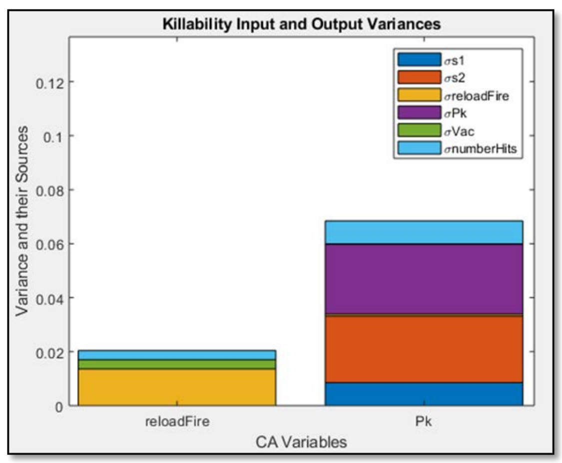

Figure 9: Reload and Fire Variance

Direct validation of aircraft survivability models has been complicated by the lack of data regarding "experimental" aircraft survivability datasets. For this effort, new datasets for aircraft survivability are unable to be gathered, and a suite of analyses and comparisons to establish the level of trust that can be placed in the proposed models by practitioners has been developed. 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 seeks to identify sensitive and relevant flight performance parameters for quantifying aircraft survivability metrics.

3.5 Aircraft Design

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. The conditions under which the proposed UAV design parameters can be demonstrated to have benefit relative to a baseline design process are being defined. 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 seeks to build a direct comparison of UAV/UAS design with and without these detailed aircraft survivability models. The results of this research 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. Sensitive aircraft survivability parameters with system sensitivity analysis are being identified. Within an aircraft sizing algorithm, sensitive aircraft survivability parameters are being related to generic aircraft design parameters. With identified related aircraft design parameters, design changes utilizing each of the traditional aircraft survivability and the new approach are being made. Traditional aircraft survivability analysis is being compared and contrasted to the newer approach in relation to aircraft design.

4 CONCLUSION

As threats have advanced, aircraft survivability is experiencing opportunities to analyze newer challenges. Looking back on the past, Ball opened the world to reliable aircraft survivability analytics with a still effective and useful method today. Now, that effort is being shepherded forward to combat newer threats with accurate representation of aircrafts' encounters. With that considered, 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, many scenarios encountering threats can be simulated. 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.

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