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6 FULL-SPECTRUM CRASH SURVIVABILITY PHYSICS-BASED MODELING
by Allen Shirley, Drew Slusser, Megan Lynch, and Bryan Cheeseman

The development, integration, and thorough testing of survivability systems for aircraft are typically inhibited by the high cost of full-system crashworthiness testing. High-fidelity modeling and simulation (M&S) is a valuable tool that can be used to supplement physical testing when time and budget constraints are present, providing for a complete and holistic assessment of system-level performance. The integration of human occupant and advanced anthropomorphic test device (ATD) models can further be used to improve the analysis. Thus, the U.S. Army Combat Capabilities Development Command’s (CCDC’s) Army Research Laboratory and Corvid Technologies, in coordination with the Joint Aircraft Survivability Program Office, have completed a project demonstrating the value of high-fidelity M&S in improving rotary-wing aircraft survivability and crashworthiness analysis. To this end, Corvid developed a model of the UH-60M Black Hawk as a demonstration of existing capabilities and to discover gaps that require method or tool improvements. This approach addresses the needs of the U.S. Army and Program Executive Office (PEO) Aviation to improve aircraft survivability and crashworthiness to meet the key performance parameters required of Future Vertical Lift platforms.

11 DEVELOPING THE FUNDAMENTALS OF AIRCRAFT CYBER COMBAT SURVIVABILITY: PART 2
by William D. Bryant and Robert E. Ball

In Part 1 of this continuing series describing the development of the new Aircraft Cyber Combat Survivability (ACCS) design discipline (published in the spring issue of the Aircraft Survivability journal), we examined the possibility that a cyber antiaircraft weapon could be developed and used effectively against modern, computer-controlled aircraft. Because of the similarities between the elements and the operations of the postulated cyber antiaircraft weapon to the similar elements and operations of the traditional kinetic energy (KE) antiaircraft weapons, such as guns with their ballistic projectiles and guided missiles with their proximity-fuzed high-explosive (HE) warheads, we used the existing fundamentals of the well-established Aircraft Combat Survivability (ACS) design discipline to begin the creation of a new ACCS design discipline. This new discipline, whose goal is the same as the ACS goal—the early identification and successful incorporation of those cyber survivability enhancement features (SEFs) that increase the combat cost-effectiveness of an aircraft—can then be used to design our military aircraft to better survive cyber antiaircraft weapon attacks.
23 **EXCELLENCE IN SURVIVABILITY: TIM HORTON**

*by Eric Edwards*

The Joint Aircraft Survivability Program (JASP) would like to acknowledge the recent passing of long-time community leader Mr. Richard A. (Tim) Horton and recognize him for his Excellence in Survivability. For more than four decades, Tim brought to his work a rare combination of operational experience, analytical insight, and proven managerial skills. A man who always wore many hats, Tim was an experienced combat aviator (of both fixed- and rotary-wing aircraft); an early survivability leader and mentor in multiple Army, Navy, and industry organizations; and a true champion of the aircraft survivability discipline.

25 **AHSS PROMISES BETTER PROTECTION, PERFORMANCE, AND COMFORT FOR ROTORCRAFT AVIATORS**

*by Bryan Pilati and Tyrone Minton*

Developers, analysts, and others have long recognized the need for a new and improved pilot seat for the aging fleet of U.S. rotorcraft. Ongoing problems, such as an expanding pilot anthropometric demographic, increased flight duration, heavier survival gear loading, and overall aging of the current seat system, have increased the occurrence of chronic injuries to rotorcraft aviators. To address these problems, The Protective Group (TPG) has been working since 2012 with the Joint Aircraft Survivability Program Office and the Army Combat Capabilities Development Command Aviation & Missile Center Technology Development Directorate — Aviation at Fort Eustis, VA, to develop a next-generation crashworthy Ballistic Resistant Adaptive Seating System (BRASS) for rotary-wing aircraft.

29 **FRANKENBERGER PRESENTED 2020 AIAA SURVIVABILITY AWARD**

*by Michael Schuck*

The American Institute of Aeronautics and Astronautics (AIAA) Survivability Technical Committee (SURTC) has selected Mr. Charles (Chuck) Frankenberger to be the recipient of its 2020 AIAA Survivability Award. The award—which was presented at the organization’s annual Science and Technology Forum and Exposition (SciTech 2020) in Orlando, FL, on 6–10 January—was in recognition of Chuck’s technical and leadership excellence in propulsion system survivability enhancement and multi-service test programs execution to evaluate and improve overall aircraft survivability.
ALEX KURTZ RETIRES

In December 2019, long-time aircraft survivability/vulnerability specialist and national and international leader Mr. Alex Kurtz retired from Government service. For more than 34 years, Alex has been a key player in the areas of weapons bay vulnerability reduction, ablative evaluation, warhead and explosive characterization, high-energy lasers, opaque and transparent armor development programs, and man-portable air defense systems (MANPADS) quantification. And the results of his vulnerability reduction contributions can be seen on many major air platforms, including the C-5, KC-46, C-17, C-130, C-130J, AC-130U Gunship III, F-16, F-22, F-35, A-10, and numerous helicopters and commercial aircraft.

Alex has also been a widely respected leader in numerous survivability-related organizations. As the Chief of the Survivability Assessment Flight, 704th Test Group, Aerospace Survivability and Safety Office, he was responsible for Title 10, Live Fire Testing & Evaluation, supporting various Air Force program offices. In addition, he served as the Chair, Co-Chair, and Secretary of the American Institute of Astronautics and Aeronautics (AIAA) Survivability Technical Committee (SURTC); as an AIAA Associate Fellow; as the Co-Chair and Air Force Representative of the Joint Aircraft Survivability Program Office (JASPO) Vulnerability Subgroup; and as the Chair of JASP’s Armor Committee. Alex was also the U.S. Technical Lead, Air Force Technical Lead, and Chairman of the International Aircraft Survivability Technology Working Group, Five Powers Long Term Technical Projects.

Furthermore, Alex has been a prolific technical writer and presenter, authoring or co-authoring many articles for the Aircraft Survivability journal, as well as for the AIAA Aerospace America “Year in Review,” and other publications and making numerous presentations on tri-Service survivability and JASP projects at various AIAA and National Defense Industrial Association conferences and symposia, as well as on various technical topics at the JASP Aircraft Survivability Short Course.

Before he joined the aircraft survivability community, Alex served as a U.S. Marine Corps officer and combat engineer platoon commander. In addition, he earned bachelor’s degrees in aeronautics from Miami University (in Oxford, OH) and in aeronautical/astronautical engineering from The Ohio State University.

Thank you, Alex, for your avid support of the survivability community and best wishes to you in your retirement.

CORONAVIRUS CANCELLATIONS

Due to the worldwide outbreak of the COVID-19 coronavirus and related travel restrictions, numerous community events that were reported on (and/or listed in the Calendar of Events) in the spring issue of the Aircraft Survivability journal were postponed or cancelled after the issue was released for printing and distribution. The editors regret any confusion or inconvenience and will pass along the dates and locations of any rescheduled events in future issues. In addition, readers are encouraged to visit the websites of, or otherwise contact, event sponsors for the latest updates and information on all upcoming community events.

HEARD ANY NEWS?

If you know of a community-related event, announcement, or other news item that you would like to submit for consideration as a News Note, please contact Mr. Dale Atkinson at daleatk@gmail.com.
The Joint Combat Assessment Team (JCAT) held its annual Phase 1 training event 6–10 January 2020 at Fort Rucker, AL. In all, 25 personnel (10 Army, 7 Navy, and 8 Air Force members) received an introduction to aircraft combat damage collection and assessment techniques. The Phase 1 graduates (shown in Figure 1) will now move on to Phase 2 training. Congratulations to all the students for a job well done.

In January, the JCAT-Army element supported the Joint Aviation Multi-Ship Integrated Air Defense System (JADS) Survivability Validation (JAMSV) on the Electronic Combat Range at the Naval Air Weapons Station in China Lake, CA. The JAMSV Team thanks the Joint Aircraft Survivability Program (JASP) Manager, Mr. Dennis Lindell, for resourcing the instrumentation provided by the Redstone Test Center.

The purpose of the test was to validate survivability effectiveness of multi-ship formations in large-scale combat operations. The JCAT team—consisting of CW4 Tyson Martin, CW4 Mark Chamberlin, CW3 Paul Olson, and CW3 Drew McCowan—provided instrumentation data collection from AH-64, UH-60, CH-47, and C-12 aircraft, which supported the test. The data will be instrumental in the development of a training support package that will be published for the joint aviation community later this year.

Unfortunately, the annual JCAT Threat Weapon Effects (TWE) training that was scheduled for 28–30 April 2020 at Hurlburt Field, FL, was cancelled due to the Government’s travel restrictions surrounding the COVID-19 outbreak. JCAT will announce future related events, dates, and locations via the Defense Information Analysis Center (DSIAC).
The development, integration, and thorough testing of survivability systems for aircraft are typically inhibited by the high cost of full-system crashworthiness testing. High-fidelity modeling and simulation (M&S) is a valuable tool that can be used to supplement physical testing when time and budget constraints are present, providing for a complete and holistic assessment of system-level performance. The integration of human occupant and advanced anthropomorphic test device (ATD) models can further be used to improve the analysis. Thus, the U.S. Army Combat Capabilities Development Command’s (CCDC’s) Army Research Laboratory and Corvid Technologies, in coordination with the Joint Aircraft Survivability Program Office, have completed a project demonstrating the value of high-fidelity M&S in improving rotary-wing aircraft survivability and crashworthiness analysis. To this end, Corvid developed a model of the UH-60M Black Hawk as a demonstration of existing capabilities and to discover gaps that require method or tool improvements. This approach addresses the needs of the U.S. Army and Program Executive Office (PEO) Aviation to improve aircraft survivability and crashworthiness to meet the key performance parameters required of Future Vertical Lift platforms.
BACKGROUND

Predictive M&S provides the opportunity to improve test device technology, inform load profiles for testing components or subsystems, and supplement the limited number of crashworthiness developmental tests. However, since responses in the airframe, energy-absorbing (EA) seats and floor technology, and the occupants themselves are highly nonlinear, this problem needs to be solved using a fully coupled and single simulation domain, rather than relying on one-way coupling between locations in the aircraft and occupant models. Highly resolved finite element meshes, sophisticated nonlinear strength and failure constitutive models, a highly scalable physics solver, and high-performance computing (HPC) resources are all needed to realize the benefits of modeling to yield a predictive capability. A full-system simulation capability also begins to fill a significant deficiency in the current testing of rotary-wing aircraft, where full-system drop testing is rare, if conducted at all.

These tools and resources have been proven effective through a similar approach for design and evaluation support for ground vehicle survivability. A similar demonstration effort started in support of Joint Program Office Mine Resistant Ambush Protected (JPO MRAP) in 2010 to extend the application of Velodyne, an explicit dynamics multi-physics solver (which was originally developed to predict post-intercept debris for the Missile Defense Agency) to the survivability of vehicle structures. Corvid continued to refine the capability and evolve the technology to not only provide predictive simulations on vehicle structural response but also provide insight into occupant injury by modeling the response of the ATD used in Live Fire Test and Evaluation.

Predictive M&S provides the opportunity to improve test device technology, inform load profiles for testing components or subsystems, and supplement the limited number of crashworthiness developmental tests.

Incorporating this additional metric enabled Corvid to provide full-system analyses to inform and supplement testing.

APPROACH

To aid in improving crashworthiness survivability technology, a finite element model was developed for use in simulating crash events with full airframes, landing gear, and seats of the rotary-wing aircraft of interest, along with occupant models. This full-system modeling approach can capture events ranging from EA landing gear and seat function, to composite airframe failure, to occupant response. In coordination with the Utility Helicopter Project Office and the Aviation Development Directorate, Corvid combined government-purpose rights data, optical metrology, and blue-light laser scan data to develop a high-fidelity structural model of the UH-60M. Particular detail in this model was paid to the landing gear, as it provides for primary energy absorption upon impact during hard landings. The tires, oleo struts, and their integration details were all considered critical and modeled in great detail.

A similar level of detail was paid to the troop seats, as these largely determine the loading experienced by occupants during a crash event. Extensive troop-seat test data from the Air Force Research Laboratory (AFRL)—collected through testing sponsored by the Defense Safety Oversight Council and the Live Fire Test Division of the office of the Director, Operational Test and Evaluation—provided validation for seat model development efforts [1, 2]. Subsystem models of the seats (both the Army’s M-variant and A/L legacy troop seats) were developed and simulated in pure vertical, combined vertical, and horizontal loading conditions for comparison with the laboratory results. Once good correlation was achieved, the seat models were then integrated into the full system-level UH-60M model. Figure 1 provides a representation of the quality of fit provided by the troop seat models.

This project also leveraged ongoing advanced human injury modeling capabilities to complete the demonstration effort. These developments expand on the high-fidelity model of the current ATD, which is being used to evaluate occupant response in crashworthiness evaluation. Corvid has also developed models for the more sophisticated Warrior Injury Assessment Manikin (WIAMan) ATD for vertical acceleration-based injury, as well as high-fidelity human body modeling with the Computational Anthropomorphic Virtual Experiment Man (CAVEMAN), which includes strength and failure parameter development for musculoskeletal systems and internal organs. Figure 2 illustrates the resolution of the CAVEMAN model, including explicit representation of all components of the musculoskeletal system with rate-dependent material models with injury specificity.
Once the full model was assembled, a range of impact conditions was demonstrated to prove out the robustness of the system-level model as well as the coupling of numerical approaches to capture soil plowing and water impact in addition to hard surface impacts.

Velodyne provides for a scalable approach to Lagrange solid element conversion to smoothed particle hydrodynamics (SPH) particles as the simulation progresses. This allows for the impact surface to be modeled efficiently as solid elements early in time and convert to SPH particles only where needed. Impact conditions, including roll and pitch conditions, were simulated in accordance with MIL-STD-1290A(AV) [3].

**RESULTS AND DISCUSSION**

While ground vehicle modeling efforts have been broadly correlated with full-system tests, these data were not available for the UH-60M. However, technicians at the Aviation Development Directorate helped to identify areas in which the aircraft normally starts to fail based on their post-incident inspections, and the model shows a similar pattern of failure. This information helped to develop confidence that the model was capturing the correct load path and major failure modes. With this limited correlation, the model was used to evaluate the aircraft performance at various impact conditions by looking at structural response and the severity of occupant injury.

A common trend was observed that echoes the lessons learned in underbody blast testing: the longer the duration of the event, the less injury that occurs as peak forces and accelerations are reduced (as long as the EA technologies are not overmatched or bottom out). In addition, orientations and ground media that spread the load out over more area of the aircraft or delay the hard crash landing often result in lower occupant injuries. Landing tail first or nose down absorbed energy in areas away from the troop seats and allowed the main
When coupled with advanced human injury modeling capabilities, these models become unique tools in the ongoing efforts to improve crashworthiness and reduce injury to aircrew and troops across all Service branches.

The flexibility of the model allows any combination of crew/troop configuration, cargo loadout, and crash orientation, enabling the model to be used in crash injury prediction, statistical analysis, and event reconstruction. When used in conjunction with technology development and integration efforts, crashworthiness evaluations can be performed faster, cheaper, and more thoroughly. High-fidelity models are resources that can help inform testing procedure, provide insight into unexpected test results, and provide repeatable and reliable subsystem and full-system comparison data that are critical for system test and evaluation.

CONCLUSION

The effort described herein has provided the blueprint for the methodologies and techniques required to develop high-fidelity models of aircraft systems when traditional manufacturing models and drawing packages are not available for government purpose use. The methods used to develop the UH-60M model could easily be applied to other aircraft and vehicles to aid in full-system analysis and testing. When coupled with advanced human injury modeling capabilities, these models become unique tools in the ongoing efforts to improve crashworthiness and reduce injury to aircrew and troops across all Service branches, especially as Future Vertical Lift requirements push to higher aircraft speeds and protection across the full range of occupant sizes, weights, and equipment loadouts.

ABOUT THE AUTHORS

Mr. Allen Shirley is currently a Program Director for Corvid Technologies. For the past 18 years, and including his prior civil service position at the Naval Surface Warfare Center, he has been developing and applying high-fidelity M&S tools and methods for lethality, vulnerability, and survivability problems across the DoD. Mr. Shirley holds a B.S. in mechanical engineering from Clemson University.
Mr. Drew Slusser is currently a Senior Analyst with Corvid Technologies. He has more than 15 years of experience supporting various DoD agencies, with a specific focus on full-system, high-fidelity finite element modeling and analysis of aircraft, ground vehicle, and missile systems. Mr. Slusser holds a bachelor’s and master’s degree in mechanical engineering from Clemson University.

Ms. Megan Lynch is currently a mechanical engineer for the U.S. Army Combat Capabilities Development Command Army Research Laboratory (CCDC ARL). She has 12 years of experience in the areas of computational biomechanics and manufacturing technology programs. Ms. Lynch holds a B.S. and M.S. in mechanical engineering from Rutgers University.

Dr. Bryan Cheeseman is currently the rapid technology transition team leader for the Materials and Manufacturing Sciences Division of the CCDC ARL. He has a B.S., M.S., and Ph.D. in mechanical engineering from the University of Delaware.

References
DEVELOPING THE FUNDAMENTALS OF AIRCRAFT CYBER COMBAT SURVIVABILITY: PART 2

by William D. Bryant and Robert E. Ball

U.S. Army Photo
INTRODUCTION

In Part 1 of this continuing series describing the development of the new Aircraft Cyber Combat Survivability (ACCS) design discipline (published in the spring issue of the Aircraft Survivability journal [1]), we examined the possibility that a cyber antiaircraft weapon could be developed and used effectively against modern, computer-controlled aircraft. Because of the similarities between the elements and the operations of the postulated cyber antiaircraft weapon to the similar elements and operations of the traditional kinetic energy (KE) antiaircraft weapons, such as guns with their ballistic projectiles and guided missiles with their proximity-fuzed high-explosive (HE) warheads, we used the existing fundamentals of the well-established Aircraft Combat Survivability (ACS) design discipline to begin the creation of a new ACCS design discipline. This new discipline, whose goal is the same as the ACS goal (the early identification and successful incorporation of those cyber survivability enhancement features [SEFs] that increase the combat cost-effectiveness of an aircraft), can then be used to design our military aircraft to better survive cyber antiaircraft weapon attacks.

We began our development of ACCS in Part 1 by identifying the three major elements of a cyber antiaircraft weapon based upon the analogous elements in the KE weapons. The three cyber weapon elements consist of (1) the software warhead, with its malware or malicious computer code, known as the weapon’s malfunction mechanism; (2) the weapon’s aircraft detection and tracking subsystem, referred to as the cyber radar; and (3) the warhead transporter subsystem, referred to as the cyber missile. This identification was followed by the description of how the warhead on a cyber weapon can kill an aircraft in flight by exploiting the aircraft’s internal cyber systems to execute the malicious computer code that causes internal critical components to malfunction, leading to one or more critical component “kills” within the flight- or mission-critical aircraft operational systems.

In this second part of the series, we first describe the actions and events that occur when one KE weapon attacks one aircraft, known as a one-on-one scenario in a man-made hostile KE environment. This is followed by a description of the ACS kill chain, consisting of the sequence of six essential scenario events that lead to a kill of the aircraft, either mission or attrition, which we then convert into the ACS probabilistic kill chain by introducing the probability that the event occurs, and the complementary probability that the event does not occur, to each of the events in the kill chain. Next, we define three of the most fundamental terms in ACS and their extension to the analogous terms in ACCS before turning to a description of the various cyber elements that could be involved in a cyber attack on an aircraft in a one-on-one scenario that takes place in a man-made hostile cyber environment.

With all of that in place, we are then able to develop the ACCS kill chain and corresponding probabilistic kill chain, which describe the sequential process of a cyber attack on an aircraft and can be used to determine the probability that the attack was successful in causing either a mission kill or a permanent kill of the aircraft. Finally, we make a brief examination of the general use of probabilistic kill chains in survivability modeling and simulation (M&S) and discuss the validity of the numerical probabilities used, with some recommendations on a more effective application.

(Note that the material describing the ACS terms and concepts throughout this article is largely taken from the second edition of the textbook The Fundamentals of Aircraft Combat Survivability Analysis and Design [2].)

ATTACKING AN AIRCRAFT WITH A KE WEAPON

For a KE weapon, a typical one-on-one scenario begins with our single aircraft flying toward, into, or over territory defended by an active KE antiaircraft...
weapon—for example, a ground-based guided missile system (such as the one shown in Figure 1) that is searching for aircraft to attack using radar, the weapon system’s target detection and tracking element. If the aircraft is detected by the searching weapon, the detected aircraft’s location is then tracked, and the aircraft is identified and targeted (if hostile).

Subsequently, if the targeted aircraft enters into the weapon’s engagement zone, the enemy may engage the aircraft by launching a guided missile, with its HE warhead, toward the detected aircraft. The launched guided missile (the warhead transport element) will then fly out toward the targeted aircraft. Eventually, the missile may come sufficiently close to an intercept with the aircraft such that the proximity-fuzed HE warhead on the missile may detonate. One or more of the fragments and the blast from the detonation (the warhead damage mechanisms) may then physically hit the aircraft, or the missile with an unexploded warhead may make a direct hit on the aircraft, followed by the detonation of the warhead on or inside the aircraft. The final phase of the attack scenario consists of the response of the aircraft to all of the damage mechanism hits.

In the end, the aircraft either survives the one-on-one encounter with the KE weapon (and continues on its mission unimpeded) or doesn’t (and is instead forced to abort the mission due to damage suffered by one or more of the aircraft’s mission critical components—which is a mission kill—or eventually crashes due to damage suffered by one or more flight-critical components and is permanently killed—which is an attrition kill).

Those aircraft that are forced to abort the mission return to base, where any combat-caused physical damage may be repaired.

In ACS, the one-on-one scenario just described is said to take place in a man-made hostile KE environment. This environment is dynamic over time, starting with the active search for aircraft to attack; and it includes the attacker’s antiaircraft weapon, any supporting equipment (such as command and control elements), and the actions and any consequences of the actions taken during the scenario (such as searching for aircraft and firing a gun or launching a missile at a detected hostile aircraft) that must be contended with by the aircraft if it is to survive while operating in this potentially lethal hostile environment.

**THE ACS KILL CHAIN**

The classic one-on-one aircraft kill chain for the KE antiaircraft weapon consists of the time-wise sequence of the weapon’s actions and the subsequent scenario events that are essential to causing an aircraft kill. The typical one-on-one kill chain is shown in Figure 2a, where the essential scenario events are in blue on the left side of the figure, with time starting at the top and moving down. Likewise, the weapon’s actions are in black on the right side of the figure. The time duration between any two sequential events is referred to as a phase or chain link between two events. The assumption is made in this kill chain that the warhead transporter makes a direct hit on the aircraft.

As shown in the figure, the weapon must first be active and searching for any aircraft that enter into the defended area. Second, the active weapon must successfully detect and identify any intruder aircraft. Third, the detected hostile aircraft is tracked; a fire control solution is obtained; and a KE warhead transporter, such as a guided missile with its onboard warhead, must be fired or launched toward the aircraft. In the fourth phase, the fired or launched warhead transporter must fly out toward an intercept with the aircraft. Fifth, given a successful intercept, the warhead transporter must hit the aircraft with the warhead’s damage mechanisms, which can either be a direct hit by the
transporter or an intercept properly oriented and close enough to the aircraft such that the warhead is effective, as in the detonation of a proximity-fuzed HE warhead such that one or more warhead damage mechanisms hit the aircraft. Sixth, and finally, the hit aircraft must be killed by the warhead’s damage mechanism hit(s).

Note that, as discussed in Part 1, the term “killed” can mean a “mission kill” that prevents the aircraft from accomplishing its mission or a permanent or “attrition kill,” where the aircraft is physically destroyed either by the hit(s) or by a subsequent crash. Thus, moving down the KE kill chain, the six essential events can be seen—from the initial activation of the weapon in preparation for the entry of any aircraft into the defended area; to the detection and identification of an aircraft; to the engagement of the aircraft (the firing or launch of a warhead transporter); to the transporter intercept of the aircraft; to the hit of the aircraft by the warhead damage mechanisms; and, finally, to the kill of the aircraft. If, after successfully proceeding down the chain to a particular phase, the next event does not occur, then none of the following actions and events can occur because the “chain” is said to be broken at that link and the aircraft is not killed (i.e., the aircraft has survived the attack).

**THE ACS PROBABILISTIC KILL CHAIN**

For our aircraft to be more survivable when flying in a man-made hostile KE environment, we need to design and operate it so that the sequence of kill chain events is less likely to be successfully completed.

---

### AIRCRAFT ENTERS COMBAT ZONE

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weapon Active</td>
<td>The active weapon searches for aircraft</td>
</tr>
<tr>
<td>Detect Aircraft</td>
<td>The weapon’s target detection sensors detect an aircraft</td>
</tr>
<tr>
<td>Launch Weapon</td>
<td>The detected aircraft is tracked, a fire control solution is obtained and the warhead transporter is launched</td>
</tr>
<tr>
<td>Successful Intercept</td>
<td>The warhead transporter ‘flies’ out toward an intercept with the aircraft</td>
</tr>
<tr>
<td>Aircraft Hit</td>
<td>The warhead transporter ‘hits’ the aircraft</td>
</tr>
<tr>
<td>Aircraft Killed</td>
<td>The aircraft is killed by the warhead transporter hit</td>
</tr>
</tbody>
</table>

---

Figure 2a. ACS Kill Chain.
What we need is a measure that an attack on an aircraft by an enemy KE weapon is successful from the enemy’s point of view. However, whether there will be a successful outcome for each of the events in the kill chain for a particular case is unknown in advance. There are simply too many unknown variables. As a result, we need to rely on event outcome probabilities. To accomplish this, we add the probability a successful event occurs, given the occurrence of the previous event, and the complementary probability a not successful event occurs, given the occurrence of the previous event, to each event in the kill chain. Figure 2b illustrates the series of kill chain events with the accompanying probabilities of success and failure and is an example of a tree diagram in probability theory. It is referred to here as the probabilistic kill chain or the kill chain with probabilities.

The two conditional event outcome probabilities for each event are mutually exclusive and exhaustive. For example, in the first event in the kill chain—weapon active—P_A represents the probability that the weapon is active and is searching for aircraft. Conversely, 1 − P_A = P_{C_A}, which is the complementary probability that the weapon is not active and therefore is not searching for aircraft. The question is asked, “Weapon Active?” If yes, then the tree diagram moves down to the right to the next branch in the tree. If no, the tree diagram moves down to the left, and the aircraft survives. The important aspect of this phase is that an aircraft survives while operating in a man-made hostile environment when the defending KE weapon is not active and, therefore, cannot detect and eventually kill our aircraft. So, any friendly operations that suppress or destroy threat weapons before they can attack an aircraft are SEFs.

The second event in the kill chain involves the two possible outcomes, with complementary probabilities, of an aircraft being detected, given that the active weapon is searching, P_{D_IA}, and an aircraft is not detected, given that the weapon is searching, 1 − P_{D_IA} = P_{C_D|A}. There are, of course, a number of aircraft design features and operational actions that can increase the probability that the weapon will not detect the aircraft (e.g., low aircraft signatures and the actions from stand-off electronic countermeasure equipment, such as noise jamming). The subsequent sequence
of events in the chain have a similar format. Finally, note in Figure 2b that the first five events capture the susceptibility phase of ACS and the last event covers the vulnerability phase (defined in Table 1).

It is important to note here that, while this probability tree diagram is simple and mathematically sound, we do not mean to imply that it is simple to determine the actual numerical probability that an aircraft will be killed. Determining each probability in the chain can be extremely difficult. Furthermore, the engagement considered represents a simple one-on-one scenario, but many engagements are far more complex and involve multiple weapons and aircraft. The main value of this model is that the more we know how a weapon kills an aircraft, the more likely we can develop SEFs that enhance an aircraft’s survivability while operating in a man-made hostile environment. With this greater knowledge, we hope to reduce any antiaircraft weapon’s effectiveness by the maximum extent possible through the use of cost-effective SEFs.

Although this probabilistic kill chain model is not meant to be a way to determine precise probabilities, if used appropriately and with caution, this model can certainly help with M&S and the selection of the most effective SEFs.

### THREE FUNDAMENTAL ACS AND ANALOGOUS ACCS TERM DEFINITIONS

Table 1 contains definitions of three fundamental ACS terms (left column) and the analogous ACCS terms (right column). These definitions are the foundation of the ACS discipline.

- **Aircraft Combat Survivability** - the capability of an aircraft to avoid or withstand a man-made hostile environment, where:
  - “to avoid” means the aircraft avoids being physically hit by one or more warhead damage mechanisms; and
  - “to withstand” means the aircraft continues to function, or eventually functions (while in flight), at a useful (Mission) or acceptable (Flight) level after being hit by one or more warhead damage mechanisms.

An aircraft’s combat survivability is measured by the probability the aircraft survives a man-made hostile environment, $P_S$.

- **Aircraft Cyber Combat Survivability** - the capability of an aircraft to avoid or withstand a man-made hostile cyber environment, where:
  - “to avoid” means the aircraft’s internal cyber systems avoid being accessed and modified, and eventually having one or more implanted malfunction mechanisms activated (referred to here as a cyber hit); and
  - “to withstand” means the aircraft continues to function, or eventually functions (while in flight), at a useful (Mission) or acceptable (Flight) level, after a cyber hit.

An aircraft’s cyber combat survivability is measured by the probability the aircraft survives a man-made hostile cyber environment, $P_S$.

- **Aircraft Susceptibility** - the inability of an aircraft on a mission to avoid a man-made hostile environment. The more likely an aircraft is hit by one or more warhead damage mechanisms, the more susceptible the aircraft is. An aircraft’s susceptibility is measured by the probability the aircraft is hit by one or more damage mechanisms, $P_H$.

- **Aircraft Cyber Susceptibility** - the inability of an aircraft to avoid a man-made hostile cyber environment. The more likely an aircraft’s internal cyber systems suffer a cyber hit, the more cyber susceptible the aircraft is. An aircraft’s cyber susceptibility is measured by the probability an aircraft suffers a cyber hit, $P_H$.

- **Aircraft Vulnerability** - the inability of an aircraft to withstand a man-made hostile environment. The more likely an aircraft is killed by the damage mechanism hits, the more vulnerable the aircraft is. An aircraft’s vulnerability is measured by the probability an aircraft is killed given one or more hits, $P_{K|H}$.

- **Aircraft Cyber Vulnerability** - the inability of an aircraft to withstand a man-made hostile cyber environment. The more likely an aircraft is killed by a cyber hit, the more vulnerable the aircraft is. An aircraft’s vulnerability is measured by the probability an aircraft is killed given a cyber hit, $P_{K|H}$.

We need to specifically address the meaning of the ACCS term “aircraft cyber vulnerability” here because of the different ways the traditional cybersecurity community uses the word “vulnerability.” One of the most fundamental concepts of ACS is that it breaks combat survivability into two parts—reducing aircraft susceptibility (which is an indication of how easy it is to hit an aircraft with a KE warhead’s damage mechanisms) and reducing aircraft vulnerability (which is an indication of how easy it is to cause a mission or attrition kill once an aircraft has been hit). This distinction between “how easy it is to hit an aircraft” and “how easy it is to kill an aircraft given that it is hit” is essential not only in understanding ACS but in developing ACCS.

We have noticed that other disciplines (such as cybersecurity) have not
adopted this two-phase model. The Committee on National Security Systems (CNSS) Glossary [3] used by Department of Defense cybersecurity professionals has no definition for “susceptibility” but instead defines “vulnerability” broadly enough to cover both “before a hit occurs” and “after a hit occurs” during an attack. Vulnerability is defined there as a “weakness in an information system, system security procedures, internal controls, or implementation that could be exploited by a threat source.” This lack of distinction between avoiding getting hit and withstanding a hit contributes to a common issue with traditional information technology (IT) systems—they may have strong outer defenses, but once an adversary gains access, there is normally little in place to prevent attackers from achieving their objectives.

A recognition of this difficulty can be seen in the increasing discussion of “cyber resiliency.” In some modern discussions of traditional IT systems, “cybersecurity” can be thought of as being focused on reducing cyber susceptibility, while “cyber resiliency” is roughly analogous to reducing cyber vulnerability. In ACCS, we chose to achieve survivability by reducing both cyber susceptibility and cyber vulnerability primarily because there are very different engineering design considerations between designing a system to not get cyber hit and designing a system to continue functioning at an acceptable level after getting cyber hit. It appears that this distinction is also now being recognized by many in traditional cybersecurity.

ATTACKING AN AIRCRAFT WITH A CYBER WEAPON

Figure 3 illustrates the man-made hostile environment associated with a cyber weapon in a one-on-one scenario. The aircraft in the center of the figure is the potential target for the cyber weapon, and the cyber attacker can send a cyber missile on any of the available cyber pathways (shown by the dashed and solid lines). The aircraft’s “attack surface” shown is a generic example of some of the types of pathways available to cyber attackers, but the details will of course change for specific aircraft, scenarios, and configurations.

For ACS, the attack surface itself is the actual exterior surface of the aircraft that can be hit by a damage mechanism. For the cyber weapon,
the attack surface typically consists of all the connection points between the aircraft and some external location in cyberspace, whether that is a wired connection or an antenna listening to a portion of the EM spectrum. These connection points then lead to the various internal cyber systems on the aircraft. The attacker does not have to send a complete warhead through the same access point; the attacker may instead send parts of it through different access points and potentially activate or trigger the assembled warhead through another completely different access point.

The attacker also does not have to immediately activate the weapon’s malfunction mechanism once the launched cyber missile hits the aircraft’s attack surface. The cyber missile can be sent at any time before or during the aircraft’s mission, and then the adversary can choose to trigger the malfunction mechanism at the most opportune time to cause the most effective aircraft kill, such as when the aircraft is in flight and has a reduced ability to withstand the malfunction effects that could lead to a crash.

**THE ACCS PROBABILISTIC KILL CHAIN**

The kill chain for cyber weapons is similar to the kill chain for the KE weapons, but it requires a few modifications to account for some of the differences between the kinetic and cyber weapons discussed in Part 1 [1]. Figure 4 shows the ACCS probabilistic kill chain after adding in the event probabilities to the ACCS kill chain.

Note that there are still six events, the first of which is that the adversary has an *active* cyber weapon, with a potentially effective malfunction mechanism, that is searching for the, or a, target. With KE ACS, it is assumed, based upon system threat analyses, that the enemy has a particular anti-aircraft weapon being modeled—such as an SA-8, which is a well-known system that many countries employ. Because cyber weapons are so much harder to discover, the probability that an adversary has actually developed one is included within this first probability that the weapon is active, because a weapon that does not exist cannot be

![Figure 4. ACCS Probabilistic Kill Chain.](image-url)
active. For example, a nation with a nascent cyber attack program and no significant aircraft industry will likely have a lower probability of being able to develop a complex cyber weapon that can kill an aircraft than a nation with both a highly developed cyber attack and avionics industry.

In the second step of the kill chain, the adversary detects the aircraft in cyberspace using its detection and tracking element, referred to as a cyber radar. The connection between the attacker and the aircraft does not have to be “live,” as the attacker’s cyber radar signal may have to cross “air gaps” where there is no continuous connection between the attacker and the aircraft. Combat aircraft do not typically have a persistent connection to the Internet, and consequently many of the potential pathways shown in Figure 2 may not be available. Defenders should not be too complacent, however, as numerous examples have shown how determined attackers can jump across seemingly “impregnable” airgaps. Probably the most famous example is the Stuxnet attack, in which the attacker was able to somehow work his way onto air-gapped centrifuge controllers in an extremely secure facility [4].

In addition, because modern combat aircraft typically need to communicate with numerous off-board systems to be effective, their attack surface—or the number of pathways to access their internal systems (i.e., establish a connection and be able to communicate with the “cyber bubble” inside the aircraft)—is typically larger than might initially be thought.

In the third step of the kill chain, the adversary, using the cyber radar, determines what pathway to the target will be used and then launches the cyber missile to transport the cyber warhead to the aircraft. A complex cyber weapon typically has a section of code designed to cause the malicious effect an attacker is trying to create (the cyber warhead with its malfunction mechanism), with that code wrapped within another section of code designed to transport the warhead to its destination along the chosen pathway, gain access to the internal cyber systems, and implant the malfunction mechanism within the aircraft’s internal cyber systems.

Because modern combat aircraft typically need to communicate with numerous off-board systems to be effective, their attack surface is typically larger than might be initially thought.

In the fourth step, the launched cyber missile transports and delivers the cyber warhead to the target’s attack surface. It subsequently attempts to access the internal cyber systems and modify the code by implanting the malfunction mechanism using the code inside the cyber missile. This step is analogous to the target intercept on the kinetic ACS kill chain because it fulfills the same basic function of delivering the warhead—cyber or kinetic—to, or into, the target aircraft.

The fifth step is the activation of the cyber weapon’s previously implanted malfunction mechanism, which is the cyber equivalent of the aircraft being hit by the KE weapon’s damage mechanisms (i.e., the cyber hit) and thus is the boundary or demarcation between the ACCS susceptibility phase and the vulnerability phase of the scenario.

It is important to note here another difference between kinetic and cyber weapons. For KE weapons, there is normally no significant time delay between the end of a successful transporter intercept with the target aircraft and hitting the targeted aircraft with the warhead’s damage mechanisms when the warhead detonates in proximity to the aircraft or physically impacts the aircraft’s skin. On the other hand, as noted previously, the cyber weapon’s malfunction mechanism can remain dormant and wait for as long as the adversary desires once it is implanted. It is as if a surface-to-air missile were shot at an aircraft and embedded itself inside without anyone noticing, but then waited 3 years until a conflict started before detonating.

However, because most in-flight combat aircraft are difficult to access from cyberspace, activating or triggering a weapon in place when desired can be extremely difficult for an attacker. If the triggering mechanism is too easy, the malfunction mechanism may be triggered early, in which case the defender will find out about the weapon and remove it. Conversely, if the triggering mechanism is too hard, the triggering may fail, and the weapon will have no effect. There is also always the danger that a defender will stumble on an implanted malfunction mechanism by accident during routine operations or that some change to the system.
The main value of this ACCS probabilistic kill chain model is that, like the ACS probabilistic kill chain model, it leads to a greater understanding of the various steps a cyber weapon must go through to be successful. With this understanding, we can attempt to reduce a cyber antiaircraft weapon’s effectiveness by searching for and selecting those cyber survivability enhancement features that result in a cyber survivable, combat cost-effective aircraft. It is not meant to be a way to determine precise ACCS probabilities, which can be more difficult to determine than the ACS probabilities. However, when used appropriately and with caution, this model can certainly help with scenario M&S, as described in the following section.

PROBABILISTIC KILL CHAINS IN M&S

Note that while the ACCS probabilistic kill chain shown in Figure 4 is principally useful as a way to understand the sequence of events during a cyber attack on an aircraft, it can also aid in the M&S of cyber attacks when searching for the “best” CSEFs by providing an estimate of the likelihood an attack by a particular cyber weapon with a specific CSEF on a particular aircraft will be successful in killing the aircraft.

While modeling the probability of a cyber attack is extremely difficult, it is simply too important to ignore. We believe the ACCS probabilistic kill chain, with its kill chain events and set of probabilities, has the possibility of turning into a promising approach when used with care and an understanding of the potential pitfalls. It’s important to note here that the probabilities of each event in the ACS kill chain can be estimated by modeling the physics of each event and then verifying the models with live fire testing. Unfortunately for ACCS, determining the probabilities for each event in the ACCS kill chain is far more challenging. As noted in Part 1, cyber weapons are complex and interactive, so it is hard to capture or determine the probability that an attack will be successful in a laboratory experiment. In addition, there is little historical data to draw upon. Thus, the uncertainty in many of the probabilities will likely be much higher than for the kinetic weapons.

Fortunately, there is an approach to mitigating these problems for both the ACS and ACCS probabilistic kill chains, Applied Information Economics (AIE), which can be used to measure and develop probabilities that can handle both high levels of uncertainty and highly limited data sets. The AIE process, which is detailed in a text by Mr. Douglas Hubbard [5], focuses on using a variety of measurement concepts and techniques such as probability distributions, expert calibration, and Monte Carlo simulations (which is discussed later) to generate useful results in environments with high uncertainty.

While modeling the probability of a cyber attack is extremely difficult, it is simply too important to ignore.

Because uncertainty will be so high, the probabilities needed to go into either the ACS or ACCS model should incorporate how exactly or inexact those values are known. A simple way of accomplishing this is to rely on a 90% confidence interval (CI) on a probability distribution instead of a single point value. So, instead of stating that in a particular scenario, the probability that an adversary would be able to implant a cyber weapon’s malfunction mechanism given a cyber missile launch \( P_{\text{missile launch}} \) is 0.472, a 90% CI might be 0.3–0.7. This means that there is a 90% chance the actual probability lies between 0.30 and 0.70.

The shape of the probability distribution also matters a great deal, and it could take any number of shapes including a uniform distribution, the famous normal distribution, a power law distribution, or any number of other possibilities. The shape will depend on a number of factors about the underlying data, and while the normal distribution may be a good place to start in the absence of more detailed information, it can be highly inaccurate for some types of data, especially where there are overpowering “outliers.” (Note, for a detailed explanation of the types of data that are not modeled well with the normal distribution, see Mr. Nassim Taleb’s text The Black Swan: The Impact of the Highly Improbable [6].)
Because there is such a small amount of hard data on cyber as an antiaircraft weapon, the probabilities in Figure 4 will largely need to be determined by experts in each level of the kill chain. Employing subject-matter experts to determine probabilities is extremely common, but it also has the potential to add large amounts of error due to the human tendency to be overconfident in assessing our own accuracy.

For example, from 927 tests in which participants were asked to assign 90% CIs to general knowledge questions (i.e., they should have gotten 90% of the questions right), they actually only got 53% of the answers correct, showing that they were significantly overconfident in their accuracy [5]. Fortunately, there is a proven way to increase the accuracy of expert predictions, by teaching them techniques to improve their accuracy and overcome typical psychological biases. Thus, as the level of calibration of experts can easily be measured by a series of tests, only calibrated experts should be used to determine the 90% CI values for the various probabilities in Figure 4.

Using CIs instead of point values provides much more useful probabilities and greater information about the possible range of values; however, the probability distributions cannot be simply multiplied together like point values. Fortunately, a technique called a Monte Carlo simulation, which was invented during the Manhattan project, easily allows the combination of distributions of probabilities [2 (p. 848), 7]. In such a simulation, random values are selected according to the probability distribution for each value, and the result is calculated. Then the process is repeated thousands of times, and the results are averaged. This type of simulation is a widely used method in the finance and insurance industries for handling data with significant uncertainty, and simple Monte Carlo calculations can easily be done on a basic spreadsheet program, such as Excel. For our purposes, the 90% CI values are input into a spreadsheet that then calculates a probability distribution using whatever distribution is selected for each of the probabilities in Figure 4. The spreadsheet then runs the scenario across however many data points are desired and provides an overall probability of a weapon systems kill given the CIs and distributions entered. Just as importantly, the spreadsheet also provides a measurement of the overall uncertainty of the final results given the uncertainty of the inputs.

CONCLUSIONS

In this second part of the ACCS series, we have given the definitions of three of the most fundamental terms in ACS and their extension to the analogous terms in ACCS. We have also:

- Described the scenario actions and events that occur in the one-on-one scenario in a man-made hostile KE environment.
- Described the ACS kill chain, consisting of the sequence of six essential scenario events that can lead to a kill of the aircraft.
- Converted the ACS kill chain into the probabilistic kill chain by adding the probability that the event occurs and the complementary probability that the event does not occur to each of the events in the kill chain.
- Provided a description of the various cyber elements that could be involved in a similar cyber attack on an aircraft in a man-made hostile cyber environment.
- Described the ACCS probabilistic kill chain analogous to the ACS probabilistic kill chain.
- Examined the use of ACS and ACCS probabilistic kill chains in M&S related recommendations for improvement.

Part 3 of this series will present the fundamentals and processes for enhancing the survivability of aircraft when threatened by a cyber weapon. The fundamentals and processes will be based upon the six ACS susceptibility reduction concepts and the six vulnerability reduction concepts that have been developed for KE weapons.

ABOUT THE AUTHORS

Dr. William D. “Data” Bryant is a cyberspace defense and risk leader who currently works for Modern Technology Solutions, Incorporated (MTSI). His diverse background in operations, planning, and strategy includes more than 25 years of service in the Air Force, where he was a fighter pilot, planner, and strategist. Dr. Bryant helped create Task Force Cyber Secure and also served as the Air Force Deputy Chief Information Security Officer while developing and successfully implementing numerous proposals and policies to improve the cyber defense of weapon systems. He holds multiple degrees in aeronautical engineering, space systems, military strategy, and organizational management. He has also authored numerous works on various aspects of defending cyber physical systems and cyberspace superiority, including International Conflict and Cyberspace Superiority: Theory and Practice [7].
Dr. Robert E. Ball is a Distinguished Professor Emeritus at the Naval Postgraduate School (NPS), where he has spent more than 33 years teaching ACS, structures, and structural dynamics. He has been the principal developer and presenter of the fundamentals of ACS over the past four decades and is the author of *The Fundamentals of Aircraft Combat Survivability Analysis and Design* (first and second editions) [2, 8]. In addition, his more than 57 years of experience have included serving as president of two companies (Structural Analytics, Inc., and Aerospace Educational Services, Inc.) and as a consultant to Anamet Labs, the SURVICE Engineering Company, and the Institute for Defense Analyses (IDA). Dr. Ball holds a B.S., M.S., and Ph.D. in structural engineering from Northwestern University.

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EXCELLENCE IN SURVIVABILITY
TIM HORTON

by Eric Edwards

The Joint Aircraft Survivability Program (JASP) would like to acknowledge the recent passing of long-time community leader Mr. Richard A. (Tim) Horton and recognize him for his Excellence in Survivability. For more than four decades, Tim brought to his work a rare combination of operational experience, analytical insight, and proven managerial skills. A man who always wore many hats, Tim was an experienced combat aviator (of both fixed- and rotary-wing aircraft); an early survivability leader and mentor in multiple Army, Navy, and industry organizations; and a true champion of the aircraft survivability discipline.

In many ways, Tim’s career in survivability started in the skies over Vietnam. After enlisting in the Army in 1961 (at the young age of 17), working his way up through the enlisted ranks, and then completing Officer Candidate School and fixed- and rotary-wing pilot training, Tim spent a decade serving as an Army command pilot, detachment and platoon commander, aircraft maintenance officer, and executive and staff officer in various assignments across the world. These assignments included two combat tours in Vietnam, where he flew the UH-1D&H and U-21A. Other aircraft he piloted included the CH-43, UH-1B, U-6A, U-8D&F, OH-13S, and C-12 (as well as numerous civilian aircraft).

These early personal operational and command experiences not only gave Tim an invaluable first-hand look at the issues and challenges of keeping aircraft flying in hostile threat environments, but they also convinced him of the critical need to incorporate survivability considerations into all aspects of aircraft research, development, testing, and acquisition.

In 1979, after returning stateside (and earning a bachelor’s degree in economics and business administration), Tim became the first Executive Director of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). To say the least, Tim set a high standard for all directors to follow, contributing to many major survivability “firsts” that continue to benefit the community today. Most notably, he was part of a team of visionaries who conceived, proposed, and (eventually) established the Survivability/Vulnerability Information Analysis Center (which is now part of the Defense Systems Information Analysis Center). He was also instrumental in the early establishment of the Joint Live Fire (JLF) program, under which all combat aircraft are now tested for survivability effectiveness.

While at JTCG/AS, Tim also served as Acting Chairman of the Countermeasures Subgroup, helping to revitalize the group and establish coordination links with the Electronic Warfare Joint Technical Coordinating Group. And he formed the Threat Review Advisory Committee, comprising representatives from various Intelligence agencies. For these and his many other achievements at JTCG/AS, Tim was awarded the Army Meritorious Service Medal.

After Tim retired from Army active duty in 1981, he became President of his own consulting firm, SIRTECH Inc. Here, he continued to support JTCG/AS projects and played a crucial role in analyzing critical technology voids and reviewing NATO programs to identify areas of common interest. Other notable projects during this time included helping to develop the plan to transition the Combat Data Information Center...
and JTCG/AS Model Repository into the newly formed SURVIAC, performing initial planning for the JLF program; and helping to develop survivability data exchange agreements between the U.S., U.K., and Germany. In addition, Tim helped incorporate aircraft survivability as a specialty of interest into the American Defense Preparedness Association’s Survivability Symposium. This incorporation would eventually give birth to the Combat Survivability Division of the National Defense Industrial Association.

In 1985, Tim became Vice President for Armament Systems International (ASI), where he managed the company’s Ridgecrest Operations; planned JLF tests; and helped coordinate the first NATO Survivability Short Course in Oberammergau, Germany. He also helped establish the Navy’s Aircraft Battle Damage Repair (ABDR) School, as well as helped develop related curriculum and an instructor’s training program.

Tim then returned to Government service as a Navy civilian, accepting a position to lead the Systems Engineering Branch of the Survivability Engineering Division at China Lake, as well as to serve as Deputy Test Director for the JLF T&E Program and as Co-Chair of the JTCG/AS Fuel Systems Committee. In these roles, he managed the Naval Aviation ABDR Program; and he coordinated survivability-related research, development, testing, and enhancements for the fuel systems, propulsion systems, structures, flight controls, hydraulic systems, etc., for many combat aircraft. These included the F/A-18, A-6, AV-8, V-22, P-3, CH-53, NATF, A-12, F-15, and F-16.

During this time, Tim was also responsible for helping to secure the funding for and coordinate the expansion of the High Velocity Airflow System (HIVAS) to full four-engine capability, as well as helping to plan and perform the first full year of the JLF Air program and the most sophisticated series of fuel ingestion tests that had ever been undertaken.

In 1988, Tim became Head of NAWCWD’s Survivability Division, assuming responsibility for all Navy and Marine Corps aircraft survivability programs. As part of his duties, he helped make many improvements to the Weapons Survivability Laboratory (WSL), including helping to implement a nine-engine airflow facility to supplement the existing four-engine facility.

Then, in 1996, Tim’s circle of responsibilities was expanded once more, when he took over leadership of NAWCWD’s so-called “Quad Division.” In this position, he was responsible for overseeing all the technical, operational, and managerial activities of four China Lake divisions: Survivability, Manufacturing, System Safety, and Reliability and Maintainability. During this time, he also served as JASP’s Navy Principal Member and chaired the JASP Principal Member Steering Group. For his efforts, he was twice awarded the Navy Meritorious Civilian Service Award (once in 1999 and again in 2004).

Tim continued in these important roles until August 2004, when he retired from Government service. But his long career in survivability wasn’t over just yet. He served for another 3 years as Manager of the SURVICE Engineering Company’s Ridgecrest Area Operation, where he managed the office’s daily operations, oversaw various NAWC survivability support contracts, helped develop an Integrated Survivability Assessment Handbook for JASP, and supported verification and validation activities for the Future Combat System program.

In the end, perhaps the greatest achievement and satisfaction of Tim’s career can be summed up in some words that he once gave in an interview. “When I used to talk to people about what satisfied them,” he said, “the most common response was, ‘We see that our work is making a difference.’ By golly, it really did make a difference, and will continue making a difference over time. So, the people, I think, and their efforts were my single greatest reward.”

Without a doubt, the aircraft survivability community owes a large debt of gratitude to Tim Horton. He helped build the discipline to what it is today; he helped mentor and inspire the next generation of survivability practitioners and leaders; and, most importantly, he helped bring America’s pilots and crewmen safely home.

JASP thanks Tim for his many years of service and offers its sincere condolences to his wife of 42 years, Beate, as well as to his son, Kristopher.

IN SEARCH OF EXCELLENCE

The Joint Aircraft Survivability Program (JASP) is always looking for deserving candidates to recognize for their Excellence in Survivability. If you know of a colleague or someone else in the community who has made, or is making, important technical or leadership contributions in the field and you would like to submit their name for consideration, please contact Mr. Dale Atkinson at daleark@gmail.com.
Developers, analysts, and others have long recognized the need for a new and improved pilot seat for the aging fleet of U.S. rotorcraft. Ongoing problems, such as an expanding pilot anthropometric demographic, increased flight duration, heavier survival gear loading, and overall aging of the current seat system, have increased the occurrence of chronic injuries to rotorcraft aviators [1]. To address these problems, The Protective Group (TPG) has been working since 2012 with the Joint Aircraft Survivability Program Office and the Army Combat Capabilities Development Command Aviation & Missile Center Technology Development Directorate – Aviation at Fort Eustis, VA, to develop a next-generation crashworthy Ballistic Resistant Adaptive Seating System (BRASS) for rotary-wing aircraft.
In 2015, the U.S. Congress also identified the need for improved rotorcraft aircrew safety and initiated the Advanced Helicopter Seating System (AHSS) program (which started as the BRASS project) [2]. In so doing, Congress directed not only the dramatic improvement of pilot ergonomics and comfort but also the increased performance of several key system capabilities, including whole-body vibration, energy absorption, ballistic protection, and autonomy.

The original intent of the AHSS program was to modernize the aging UH-60 fleet pilot/copilot seat solution. Over the course of that effort, new direction and support adjusted the design toward the AH-64 platform. As of this writing, the initial Technology Readiness Level (TRL) 6 technology demonstration (TD) units for the AH-64 have begun production and are scheduled to be tested in 2020. In addition, TPG has secured funding to continue the UH-60 development program begun under BRASS with the ultimate goal of a fully qualified seating system by late 2023. The AHSS TD units will be used to validate the claims of the various integrated components against a refreshed design specification. The findings of the TD tests will drive the UH-60 development and qualification efforts moving forward under AHSS and will ultimately serve as a springboard to U.S. Army Future Vertical Lift (FVL) platforms.

INTEGRATED TECHNOLOGIES

From the onset, the AHSS program has had the ultimate objective of reducing pilot fatigue and potential for injury while accommodating an ever-expanding pilot population. TPG has used the most recent Anthropometric Surveys [3] to drive the updated 5th- to 95th-percentile occupant dimensions. Consultation with the U.S. Army Utility Helicopters Project Management Office has yielded updated occupant gross weights in excess of those historically associated with rotorcraft pilots, expanding the maximum, fully equipped, occupant weight from 250 lbs to more than 330 lbs for the 95th-percentile male.

Another primary driver for the AHSS design was the 95th-percentile female hip width, which increased from 17.5 inches to 19 inches. Using the updated pilot anthropometric data along with the guidance of the “Full-Spectrum Crashworthiness Criteria for Rotorcraft” report [4], TPG began to investigate technologies that would allow for a compact, yet survivable seating solution within the notional aircraft constraints of the UH-60 and AH-64 platforms. Figure 1 provides a preliminary depiction of the AH-64 integration.

Energy Attenuation and Crashworthiness

Typically, crashworthy rotorcraft seating has used simple, lightweight systems to accomplish the goal of energy attenuation. Unfortunately, those simple systems, while generally effective, do not adequately protect the broad envelope of users or cover the crash severity level necessary to advance the state-of-the-art in crash-worthy seating technology. Thus, for AHSS, a variable load, automatically selectable profile energy absorber (EA) system (from the Arizona-based Safe Inc.) was chosen. This EA system allows for a significantly wider and on-the-fly adjustable energy attenuation system. It is controlled by a microprocessor to detect the occupant’s seated weight and seat height position and allow for the selection of an optimum energy profile, which will maximize stroke and minimize lumbar loading during a crash event.

In addition, given specific state data input from the aircraft, the EA system can be made to adjust profile selection immediately ahead of a predicted crash event, thus optimizing energy attenuation just moments prior to impact. The AHSS TD units will demonstrate the ability to modify EA profile in flight but...
will not include full autonomy under the UH-60 qualification effort due to a lack of data stream from that platform. Data systems will be designed around the UH-60’s data-bus and the FVL-compliant Open Architecture scheme.

As occupant-borne gear loads continue to increase, concern has also been raised about how this increase might affect lumber loading and ultimately the crashworthiness of the seat. To combat this additional loading, the AHSS has incorporated a modified flight vest with an automatic pretensioning restraint system. The integrated vest/restraint works to decouple the load attached to the vest and transfer that load directly to the restraint webbing.

This pretensioning system also acts to move the restraint closer to the occupant torso, minimizing the chance of the webbing crushing gear or potentially injuring the occupant. The system works similar to an ejection seat restraint in that it can retract any excess webbing and lock the standard MA-16 (from the Iowa-based Cobham Mission Systems) type of omnidirectional reel while also pulling the occupant into a more upright position before the seat begins to stroke through the EA. This prepositioning should aid in reducing any head strike and Head Impact Criteria (HIC) concerns around the seat location.

**Whole-Body Vibration**

At the time the BRASS/AHSS program was initiated, several studies had been released relating aircraft vibration to long-term health effects in military helicopter pilots. These effects were found to equate to hundreds of millions of dollars in long-term medical expenses [1]. Accordingly, to combat whole-body vibration, the AHSS includes active vibration-dampening capability, which has been tested and flown in U.S. Navy UH-60S and -60R variants. This technology has been proven to reduce felt vibration below the 12-hr exposure limits set by ISO 2631-1 via flight and ground test (under contracts managed by the Naval Air Systems Command). The Active Vibration Attenuation Seat Suspension (AVASS) (from the Maryland-based InnoVital Systems) system uses a magnetorheological damper in the seat guide tube to counter aircraft vibration before it reaches the seat bucket.

**Ergonomics**

The primary mission directive levied on the AHSS program from inception has been to decrease fatigue and increase pilot endurance as mission durations have been steadily increased over the last few decades. To improve the ergonomic function of the seat, TPG has incorporated multiple independent adjustment points (both seat back and seat pan angle) as well as an improved cushion system (from Maryland-based LME) into the seat bucket. This incorporation acts to alleviate hot spots and pressure points under the ischial tuberosities while minimizing overall seated pressure. Working together with industry partners, the AHSS program has included a robust ergonomic study (using U.S. Army pilots) to determine the correct cushion configuration, yielding low pressures without compromising crashworthiness of the seat. Thermal transfer into and out of the cushion system was also taken into account to improve overall mission comfort.

**Ballistic Performance**

TPG is leveraging many years of experience in the aviation armor field to develop a ceramic composite armor system that has reduced areal density over the legacy seating system for the same threat specification. Advances in material processing allow for a more complex ceramic component to better aid in seated ergonomics while mitigating the need for extraneous tooling and added manufacturing lead times. The proposed armor system comprises a boron or silicon carbide strike face encapsulated in a structural composite shell. The bucket is then lined with the newest version of ultra-high molecular weight polyethylene (UHMWPE) for fragmentation and spall protection. This modern composite armor approach is expected to yield an armored seat bucket approximately 20% lighter than the legacy system.

**Autonomy**

When discussing crashworthiness and capability, the issue of user error is a common theme. In current seat systems, the user is required to know his/her loadout weight and seated weight to properly adjust the energy attenuation system in the given aircraft. This simple system, however, does not account for seated height and the respective allowable stroke distance. It also does not allow for changes in flight or preceding a crash event. The AHSS will mitigate this user error by automatically weighing and monitoring seat...
position (to include back and pan angles) at startup (baseline, zero-power failsafe) as well as continuously throughout a mission to adjust the EA system for optimal safety of the occupant. In cases where the aircraft is able to provide vertical speed, orientation, proximity data, or any combination of those, the seat will be capable of adjusting the EA profile ahead of a predicted crash or hard landing event.

**CAPABILITY EXPANSION AND CROSS-PLATFORM COMPATIBILITY**

TPG anticipates major leaps forward in airframe safety systems and plans to design placeholders in the AHSS that will accommodate those systems in the future. Capability such as crash prediction hardware or software can be used to preset the AHSS for a given predicted crash impulse, even if that event is as mild as a hard landing. It may also be possible to leverage the ongoing AHSS qualification effort to validate some of these emerging capabilities in conjunction with the seat system. Currently, the AHSS has a well-defined direction to airworthiness, but the program is open to expansion toward a fully universal architecture that can be used across many aviation platforms (FVL platforms included), as well as incorporated into any number of technology and safety capabilities required by an individual platform.

**ABOUT THE AUTHORS**

Mr. Bryan Pilati is the Project Engineer for the BRASS/AHSS projects at the U.S. Army Combat Capabilities Development Command Aviation & Missile Center Technology Development Directorate – Aviation. He has been with the U.S. Army for more than 34 years and is responsible for development of crashworthy seating, restraints, landing gear, and fuel systems across all Army aviation platforms. Mr. Pilati has B.S. in mechanical engineering technology from Old Dominion University and an M.S. in engineering management from George Washington University.

Mr. Tyrone Minton is the Program Manager for the AHSS project at The Protective Group (TPG) and has led the BRASS/AHSS programs since their inception in 2012. He has been with TPG for 10 years and is responsible for the development and integration of armor systems across multiple platforms, including the UH-60, CH-47, and CH-53K. Mr. Minton has a B.S. in aerospace engineering from Arizona State University.

**References**

The American Institute of Aeronautics and Astronautics (AIAA) Survivability Technical Committee (SURTC) has selected Mr. Charles (Chuck) Frankenberger to be the recipient of its 2020 AIAA Survivability Award. The award—which was presented at the organization’s annual Science and Technology Forum and Exposition (SciTech 2020) in Orlando, FL, on 6–10 January—was in recognition of Chuck’s technical and leadership excellence in propulsion system survivability enhancement and multi-service test programs execution to evaluate and improve overall aircraft survivability.
Chuck’s career, encompassing more than 30 years, has been focused on supporting the survivability community in the areas of aircraft propulsion system survivability and Live Fire Test & Evaluation (LFT&E). His technical achievements have been instrumental in developing propulsion system technologies and analysis methodologies to reduce aircraft vulnerability to combat threats and in prolonging engine life during normal operation. These developments include methodologies for identifying engine combat vulnerability and for damage detection and mitigation during engine service life. His accomplishments in these areas have greatly benefitted both military and commercial aviation.

As the current Systems Vulnerability Branch Head for the Naval Air Warfare Center Weapons Division (NAWCWD) in China Lake, Chuck provides oversight and management of the Weapons Survivability Laboratory (WSL), leading his organization in maintaining an impressive array of survivability testing capabilities. For example, he helped initiate development of a spin fixture, which evolved into a dynamic test capability for helicopter drive trains, including shafts, gearboxes, and rotors. He is also continuing to spearhead future efforts to expand capabilities into emerging threats, including directed energy (laser and radio frequency). He was also a lead figure in the merger of Air Force and Navy vulnerability LFT&E test capabilities at WSL.

In addition to his current NAWCWD Branch Head role, Chuck has also assumed numerous other leadership roles within the U.S. Navy and other organizations. These roles have included serving as a Navy member on the Joint Aircraft Survivability Program (JASP) Vulnerability Reduction Subgroup, as Chairman for the JASP Vulnerability Reduction Subgroup Propulsion Committee, and as a Navy member of the Federal Aviation Administration (FAA) Catastrophic Failure Prevention Program.

Chuck’s unparalleled expertise in engine vulnerability began with his efforts as lead for turbine engine vulnerability programs. Serving as test engineer for propulsion efforts during the V-22 and F/A-18E/F LFT&E programs, he gained early insight into the world of digital engine controls. He worked with the FAA Technical Center and the Navy through an Interagency Agreement (IA) and led efforts to collect data for, and define the characteristics of, an uncontained engine failure. This work eventually led to the development of the Uncontained Engine Debris Damage Assessment Model (UEDDAM), its proposed use for compliance with FAR 25.903 (d) rotor burst assessment, and revisions to the FAA’s Advisory Circular 20-128A for multiple fragment threat analysis.

Both safety and LFT&E issues were addressed during the C-5 Reliability Enhancement and Re-Engining Program (RERP) using FAA-endorsed methodologies that stemmed from Chuck’s work, answering critical
questions about safety and vulnerabili-
ty of the upgraded engines due to cascading damage. Through a second IA, the Navy increased its involvement in the Catastrophic Failure Prevention Program. He coordinated participation from the FAA, the Navy Propulsion RDT&E, NASA Glenn, and NAWCWD, resulting in a very successful engine test evaluating on-engine detection methodologies. Numerous FAA technical reports were published as a result of this program.

Chuck’s initial role on the Joint Strike Fighter (JSF) LFT&E program was as the JSF Propulsion Vulnerability Lead. His oversight included responsibility for all propulsion LFT activities and participation in Preliminary Design Reviews and Critical Design Reviews for the Pratt & Whitney F135 and General Electric F136 vulnerability teams. He led and managed propulsion test efforts and contractor efforts addressing Survivability Engine Controls; and he later became the JSF Vulnerability and LFT Team Lead, coordinating activities with the F-35 Joint Program Office, contractors, the Air Force, and the Office of the Secretary of Defense’s Director, Operational Test and Evaluation. The program—which encompassed four Pratt & Whitney engines and three full-scale test articles, in addition to many component and subcomponent test assets—culminated with successful full-up system-level (FUSL) testing, including FUSL testing of the Short Take-Off and Vertical Landing (STOVL) propulsion system.

Chuck’s organization was one of only three in the U.S. to run the full-up STOVL propulsion system. His leadership and technical oversight ensured that the vulnerability of all three JSF variants was fully documented and assessed against the stated objectives in the Operational Requirements Document, Aircraft Specification, and Test and Evaluation Master Plan. Of further note was the successful completion of five man-portable air defense system (MANPADS) live fire tests, which included impacting fully operating engines. Chuck’s consistent, superior performance and meticulous attention to detail was instrumental in delivering the most tested and analyzed tactical aircraft of all-time.

Chuck also developed and directed JASP projects during the highly successful Survivable Engine Control Algorithm Development (SECAD) program. Through the use of digital engine controls, SECAD demonstrated state-of-the-art engine damage detection and mitigation methodologies using production engine sensor and control hardware. These efforts resulted in the development of a methodology to detect engine gas path damage. This technology has since been applied to commercial high-bypass-ratio turbofan engines and small helicopter turboshaft engines, and the work was highlighted at an IEEE Symposium and in Aviation Week magazine.

Congratulations, Chuck, on this well-deserved award! 

ABOUT THE AUTHOR

Mr. Michael Schuck is the Manager of the SURVICE Engineering Company’s Dayton Area Operation. He has more than 15 years of vulnerability expertise evaluating fixed-wing and rotary-wing platforms against kinetic energy, directed energy, and nuclear threats. He has also been active in AIAA for more than 12 years, serving as the Chair, Vice Chair, and Secretary of the AIAA SURTC.
ATTENTION:
Due to the many last-minute event postponements, cancellations, and travel restrictions related to the COVID-19 outbreak, readers are encouraged to double-check with event sponsors and websites to confirm the status of an event before making associated travel reservations and other plans.

JUNE
2020 AVIATION Forum
15–19 June (Online)
https://www.aiaa.org/aviation

“Introduction to Brawler” 2020 Training
16–19 June in Lexington Park, MD

JULY
MegaRust 2020
28–30 July in San Diego, CA
http://www.navalengineers.org/Symposia/MegaRust-2020

SEPTEMBER
2020 STRIKE Challenge
1–3 September in Alton, VA

2020 Air, Space & Cyber Conference
14–16 August in National Harbor, MD
https://www.afa.org/events/calendar/2020-09-14/air-space-cyber-conference

Note
The inclusion of an event in this calendar does not necessarily reflect the endorsement of that event or its sponsoring organization(s) by the Joint Aircraft Survivability Program Office or the Defense Systems Information Analysis Center.