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An Enhanced Optical Sensor Instrumentation System to Improve the Survivability of Armored Vehicles

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ABSTRACT

The Optical Warhead Lethality Sensor Suite (OWLSS) was designed specifically for tracking dense, fast fragment fields generated in warhead arena testing. OWLSS is an optimized hardware/software solution for measuring correlated properties of detonating warhead fragment distributions. The OWLSS automated track algorithm returns time-dependent 3D position, velocity, size, aerodynamic drag, and mass estimates for each fragment tracked. These data products fill a significant gap in our ability to characterize munitions for weapon effectiveness modeling. Furthermore, the system is modular and can be reconfigured for many tracking applications. In this paper, we present an overview of legacy arena measurement techniques, an overview of the OWLSS optical tracking approach, and we discuss how OWLSS can be employed to collect test data needed to improve the survivability of armored vehicles.

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1. INTRODUCTION

The US Army is actively pursuing Vehicle Protection Systems (VPS) to augment the defense of Abrams tanks and other armored vehicles [1-2]. These systems are expected to employ active and passive systems for avoiding, defeating, or mitigating threats [3]. A combination of active and reactive systems is often needed to enhance survivability, requiring trades in effectiveness and suitability with power and weight requirements to identify optimal configurations for differing combat scenarios. High resolution lethality models driven by highly resolved, correlated fragment data collected during munitions and engagement test events will ensure that optimal solutions are employed for the environments in which the armor vehicles are expected to operate.

Fragmentation driven Lethality, Vulnerability, and Survivability (LVS) assessment modeling has historically focused on: A) fragment distribution properties generated in a static detonation, and B) fragment impact interaction with a given target. Very little research has been published on explosively generated fragment aerodynamics required to propagate the fragment from point A to

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point B [4-5], nor investigate dynamically induced detonation (e.g., impact or blast) changes to a warhead's initial fragment distribution properties. Limited understanding in these areas is further compounded by a lack of experimental data and, more specifically, a lack of the right kind of experimental data. Legacy warhead characterization approaches do not measure all required fragment properties, nor do these techniques measure correlated properties. Mass and velocity are measured on mutually exclusive subsets of fragments. Furthermore, no aerodynamic information is captured. Without correlated kinematic, physical, and aerodynamic fragment property measurements, mathematical inconsistencies are introduced into weapon effectiveness modeling that require analysts to be overly cautious with their assessments.

Torch Technologies developed an optimized hardware/software approach to overcome fragment measurement deficiencies in legacy static arena warhead testing for the Office of the Secretary of Defense (OSD) Advanced Weapon Effects Test Capability (AWETC) project. This approach is realized in the Optical Warhead Lethality Sensor Suite (OWLSS) system [6]; designed specifically for tracking dense, fast fragment fields from warhead munition detonations. OWLSS includes high-speed video cameras that combined with advanced image processing and tracking algorithms can return correlated kinematic, physical, and aerodynamic information on many thousands of unique fragments generated in an explosive event. The system is modular and configurable to a wide range of test scenarios. In the following sections, an overview of legacy warhead characterization measurements is presented followed by a discussion of the technologies and methodologies employed in the OWLSS system and results from live-fire testing. In the final section, OWLSS system support of dynamic VPS testing to enhance ground vehicle survivability is presented.

2. LEGACY APPROACH TO WARHEAD CHARACTERIZATION

Standardization procedures for warhead characterization arena testing defined in the Joint Munitions Effectiveness Manual (JMEM) [7] were developed in the 1960's and have remained largely unchanged since. The JMEM warhead characterization premise is based on fragments hitting physical structures constructed around the munition (i.e., "the arena" shown in Figure 1). Fragments are captured by soft-catch systems, usually large Celotex panels, that require manual retrieval after the event. Physical recovery supplies size, shape, and mass characterization, although often only mass is measured in the interest of time and money. Furthermore, physical structures quickly become too cumbersome for all but the smallest weapons. Testers typically collect less than 5% of the total weapon case mass and collect velocity measurements on ~ 1% of the fragment dispersion on medium-to-large weapons.

Figure 1: A weapon arena with 180° soft-catch bundles surrounding a warhead placed at the center of the arena.

Flash panels and/or velocity screens provide single point, time-of-arrival (TOA) measurements that are used to calculate fragment average velocity over the distance traveled. However, TOA measurements cannot be correlated with specific fragments (i.e., mass) and, when using flash panels, these measurements are captured on a different subset of the fragment distribution than the subset captured and weighed. A single TOA measurement for an unknown fragment introduces a dilemma, since LVS models require initial velocity input. There are a large family of admissible trajectories that match at a single point in space-time but diverge everywhere else. The family of trajectories that match the average velocity measurement are governed by the fragment's initial velocity and aerodynamic drag properties. Two such trajectories are shown in Figure 2. Each physically admissible trajectory has a unique initial velocity. Furthermore, even at the one matching space-time point, the instantaneous velocity (i.e., slope) is different for each trajectory (see Figure 3). Therefore, even though the average velocity might be measured to high precision (< 1% is common), without precise knowledge of the trajectory profile, the instantaneous velocity needed for LVS modeling can differ by 100% or more even at the measurement location, as shown in Figure 3.

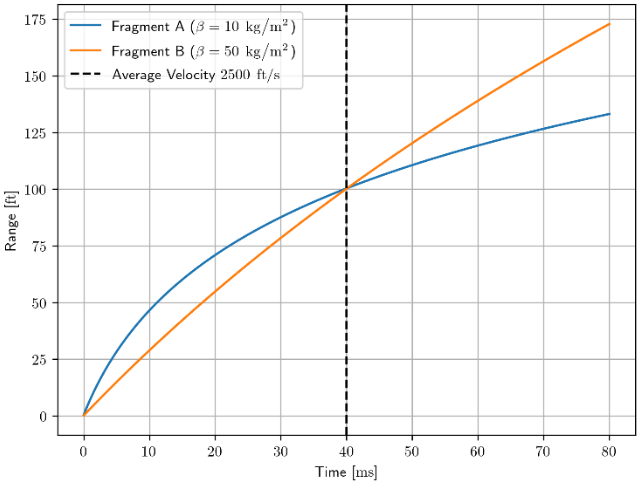

Figure 2: Two realistic fragment trajectories that intersect at the same space-time point (same average velocity at that single point).

To constrain the trajectory profile indeterminacy, JMEM [2] employs an analytic approximation for the aerodynamic trajectory of a point mass along a line (i.e., drag but no lift) to solve for the initial velocity given a known average velocity at a specific distance. Unfortunately, since nothing else is known about the fragment that generated the TOA signal, the required aerodynamic information is approximated with average recovered mass in the relevant polar zone and standard reference table quantities. Therefore, the quality of the JMEM initial velocity calculation is inherently unknown, as well as, the uncertainties in the propagated velocity solutions. These known deficiencies in legacy techniques led the Office of the Secondary of Defense (OSD) to invest in new technologies, such as OWLSS, to improve warhead characterization for weapon effectiveness modeling.

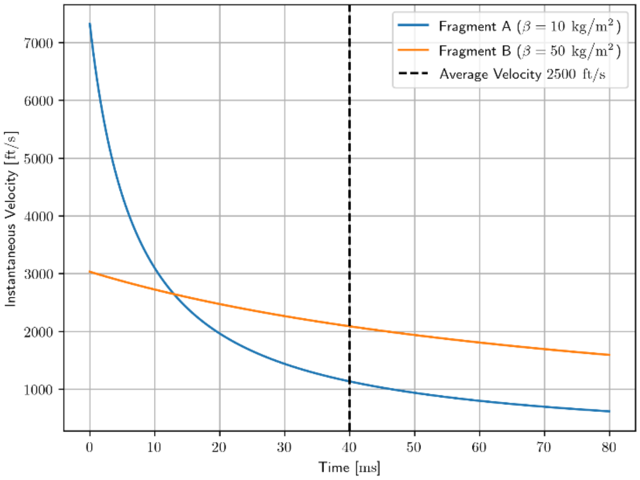

Figure 3: Instantaneous velocity for the two trajectories shown in Figure 2.

3. OWLSS

OWLSS fragment tracking technology development began in 2012 under a Small Business Innovative Research (SBIR) grant from the Air Force Research Laboratory (AFRL). This work has culminated in the OWLSS warhead characterization system developed for the AWETC project through OSD's Central Test and Evaluation Investment Program (CTEIP). The first OWLSS system was delivered to the 96th TW at Eglin Air Force Base in 2019. Two more systems are in development for the Army (Redstone Test Center) and Navy (Naval Air Warfare Center Weapons Division at China Lake) for delivery in 2020.

The OWLSS system includes up to 16 high-speed cameras deployed around the test arena in stereo pairs. Figure 4 shows a full system layout that utilizes eight OWLSS dual camera assemblies deployed in stereo configurations surrounding a weapon arena. Complete characterization of the warhead requires that, at a minimum, the debris properties are measured from nose (0° polar angle) to tail (180° polar angle). Fragmentation of standard weapons assumes that the debris distribution is radially symmetric about the target centerline, such that extrapolation techniques can be combined with partial radial angle coverage to describe the distribution properties. However, new weapon designs with targeted non-symmetric debris fragmentation properties place a premium on measurement coverage to reduce test costs. The lower/upper dual camera configuration that OWLSS employs is particularly valuable in this regard, since it enhances the spatial volume coverage around the weapon. The full system is designed for 0-180° polar angle coverage at the requisite AWETC resolution requirement (2-mm, 5-mm, or 7-mm minimum fragment size depending on the weapon explosive content). However, OWLSS is a modular architecture that is designed to handle 1-to-n stereo camera pairs, such that, the total number of cameras and the camera configuration can be optimized to meet test requirements.

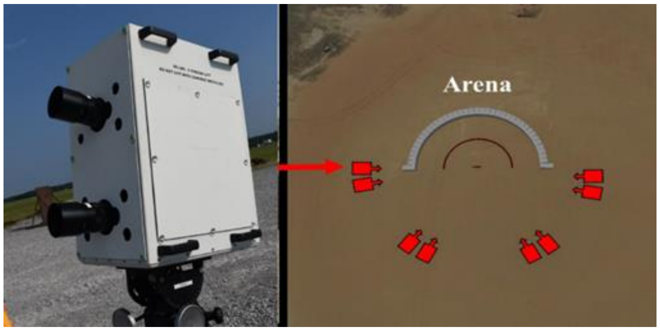

Figure 4: OWLSS Instrumentation System. Dual cameras mounted on a single tripod (left) represented by a red camera icon on the right. Eight dual camera assemblies (16-cameras) comprise the full system.

3.1. Methodology

High-speed cameras offer many advantages over standard arena panels for non-intrusive fragment measurements. Most notably, 10's-100's of stereo image measurements can be captured on unique fragments to characterize both the aerodynamic trajectory and physical characteristics of the fragment.

The major stereo tracking functions in the process are:

1) Camera registration
2) Fragment detection
3) Track construction
4) Trajectory state estimation
5) Physical characterization

Camera registration calibrates the line-of-sight pointing for each camera in a specific coordinate system (e.g., target-centric coordinates). The registration provides the mapping function to transform between 2D pixel measurements and 3D pointing vectors. The standard camera calibration approach for stereo vision applications is the pinhole camera model [8]. The model requires derivation of intrinsic camera parameters (e.g., effective focal length) and extrinsic parameters (3D location and rotation). The OWLSS implementation of the pinhole camera model utilizes an array of fiducial markers that are surveyed in the target coordinate system and imaged by the lower cameras in each assembly to solve for the calibration model parameters. Given a set of at least four correspondences between 2D image points and 3D object locations, a unique set of parameters can be found that minimize the errors between the expected image locations and actual image locations. However, the typical number of correspondences used for lower camera calibration is 6-8. The upper cameras in the dual-camera assembly are pointed skyward, such that, the scene is not easily fiducialized. Therefore, a modified procedure is implemented to solve for the upper camera calibration parameters. The upper camera pointing relative to the lower camera is rigidly fixed within the camera assembly. The upper camera calibration is initially boot-strapped from the lower camera's pointing with this known relative pointing matrix. Any remaining biases are corrected using objects detected (e.g., fragments) in the overlap region of the lower/upper camera fields-of-view. OWLSS camera calibration accuracy is typically sub-pixel, which at the standard 50-70 m standoff, equates to 1-2 cm in 3D triangulation uncertainty.

Calibration accuracy can be improved by either imaging at higher resolution (typical is 100 μrad pixel instantaneous field-of-view) or increasing the bi-static angle between the stereo cameras (typical is 3-5°). However, increasing resolution decreases the total imaging volume for a given camera, since the number of pixels is fixed, and heightens the potential for motion smearing of fast objects thus decreasing 3D position accuracy. Increasing the stereo bi-static angle escalates the complexity of the measurement-to-track association problem when the scene is cluttered and/or includes many track objects, which can lead to fewer good tracks. It is important to weigh each of these factors when developing and optimizing a measurement concept for a given stereo tracking scenario or application.

Fragment detection requires an intensity change in the image sequence. This can either be a brightening or darkening of a pixel area relative to the previous frame. For large volume, open air, day-time testing, the most natural approach is to utilize the sky as the "fixed" background to monitor for changes. While both bright and dark fragments are observed, the preponderance of fragments appear darker than the sky. "Negative contrast" detection has the added advantage of providing a better geometric description of the fragment, since it is essentially blocking light from the background. OWLSS automated detection algorithms have been optimized for sky backgrounds and have been shown to be robust against all types of lighting conditions from no-clouds, partial clouds, to onset of thunderstorm clouds.

Track construction: The primary challenge for optically tracking a fast-moving fragment field generated by a warhead detonation is to correctly assign fragment detections to tracks in a cluttered environment. This includes correlating detections between stereo cameras, as well as, from one camera frame to the next. High-density fragment fields generate many closely spaced objects on the focal plane, including fragments with crossing trajectories and unusual aerodynamic motion that can easily confound an automated measurement assignment algorithm. Significant progress has been made towards solving this problem as shown in Figure 5. In fact, OWLSS automated track algorithms have successfully returned over 6,000 individual fragment tracks from a single stereo camera pair.

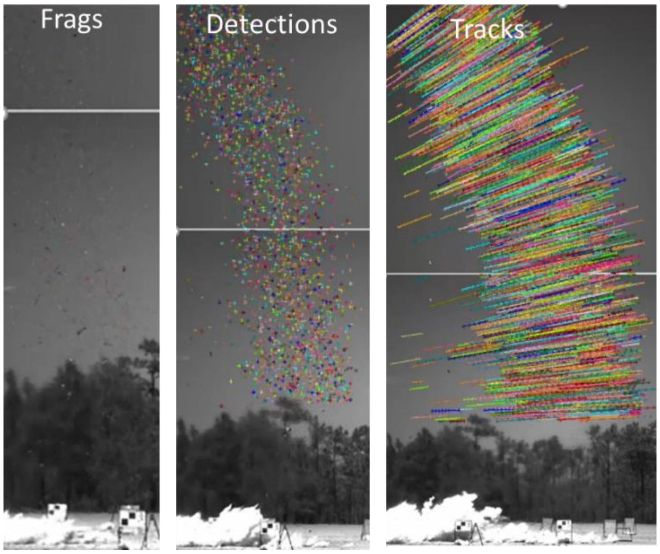

Figure 5: Image panes highlighting the processing from raw imagery to fragment detections to unique fragment tracks.

Trajectory State Estimate: Each fragment track includes a set of temporal 3D position measurements. An inherent value in optical-based methods relative to legacy techniques is that these measurements accurately constrain the fragment trajectory throughout the measurement volume. Therefore, the 3D position data can be fit to an aerodynamic trajectory model and the measurements condensed into a set of parameters (i.e., initial velocity with correlated drag properties) that LVS models can use to accurately propagate individual fragments. OWLSS standard approach employs optimal state estimation techniques to fit the data to a 7-state aerodynamic model. The model reduces the data set to the initial 3D position, initial 3D velocity, and the aerodynamic quantity ρ/β, where ρ is the air density and β is the ballistic coefficient.

It is important to note that the fragment aerodynamic properties are derived solely from the 3D position time-series and no physical description is required. While not all fragment trajectories fit this simple model, it provides an excellent description for a large majority of tracks. OWLSS standard track quality metrics require that the median Euclidean residual between the time-dependent position measurements and the propagated trajectory solution is less than 10 centimeters. Higher order aerodynamic models that include lift, velocity-dependent drag, and air-blast profiles have been developed for special cases.

Physical Characterization: OWLSS includes automated image processing algorithms to derive the time-dependent projected areas A_p from each tracked fragment detection. The size information is then combined with the aerodynamic ballistic coefficient to estimate mass ($M = \beta * A * C_d$). The advantage in this approach is that it does not require a priori fragment material information. Furthermore, estimating fragment volume from poorly resolved projected areas is inherently uncertain. The drawback is that the reference drag area ($A * C_d$) is unknown. It is approximated using the median projected area derived from the imagery and the JMEM C_d table values[2]. While much work remains in improving and validating optical-based mass estimation, the OWLSS aerodynamic approach works surprisingly well. Live-fire test results from munitions with pre-formed fragments and limited dedicated testing on natural fragments demonstrate that, on average, estimates are typically within 25% of the true mass. The OWLSS system is unique in that it delivers per-fragment correlated properties (initial velocity, mass, and aerodynamic drag) on a statistically relevant sample of the fragment distribution.

3.2. Live-Fire Testing

Live-fire testing has been critical to OWLSS technology development. The OWLSS system has participated on over sixty arena tests with munitions that range from small rockets to thousand-pound bombs, including a wide variety of new warhead designs that incorporate multiple pre-form fragment variations and other exotic materials. These full-scale tests have been supplemented with dedicated tests, such as, small custom “pipe-bombs” and single fragment 40-mm powder gun shots to test specific aspects of the algorithms.

Verification and Validation (V&V) of the OWLSS results are challenging. Legacy techniques provide limited measurements for comparison and, to further complicate matters, the measurement volumes rarely overlap. Therefore, statistical comparisons generally must suffice. Comparisons to range TOA measurements have demonstrated good correlation in both angular distributions and peak values. For example, Figure 6 presents a polar angle distribution comparison of range TOA-type average velocity measurements with OWLSS measurements, where the OWLSS trajectory solution was propagated to the same panel distance to calculate average velocity. The overall shape and magnitude of the velocity envelope shows good agreement in the polar zones that both systems collected data. Note that the peak of the angular distribution is pushed towards the nose (0°), as expected for a tail-initiated detonation. Furthermore, the OWLSS system is capable of tracking fragments behind the blast wave, which legacy measurements typically ignore, since the blast wave impact on the panels leads to spurious results.

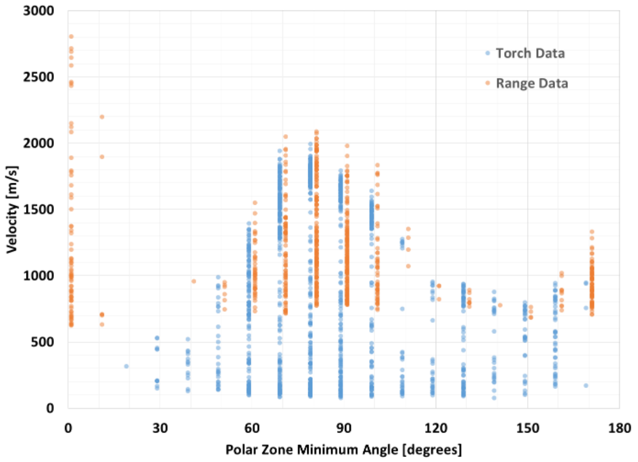

Figure 6: Average velocity polar angle distribution comparison.

The results of a dedicated V& V test are shown in Figure 7. An additional set of flash panels were placed in a position that allowed OWLSS to track fragments prior to impact. The OWLSS trajectory solutions were propagated to predict the impact location and timing of the hit on the flash panel and then compared to an independent analysis of the flash panel data. The mean difference in impact location was 4.4 cm with a 2 cm standard deviation and the impact timing between the analysis agreed to within 60 microseconds, which was less than the flash panel camera frame period.

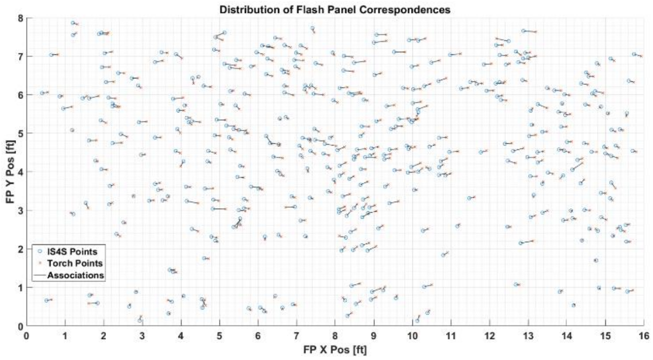

Figure 7: 1-to-1 comparison of OWLSS predicted fragment impacts on a flash panel to an independent analysis of the flash panel imagery.

Another gauge of consistency is to compare track results obtained from the independent analysis of camera pairs that view the same spatial volume. Initial V&V work included overlapping spatial measurement volumes with multiple camera groups for this purpose. Results from such a test are shown in Figure 8. Two standard OWLSS camera groups view nearly the same spatial volume (polar, radial angles) while a third pair (flash panel results shown in Figure 7) view the same polar angles but not radial angles. However, the debris distribution is expected to exhibit radial symmetry. Propagated fragment positions from each camera system are shown at one point in time after roughly 50-meters of flight. Note that the leading edge and width of the beam spray are in good agreement between all three systems. Furthermore, the flash panel cameras (blue dots) were in excellent 1-to-1 agreement with the range measurements.

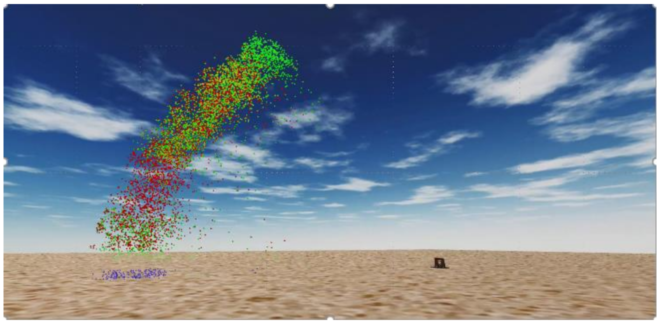

Figure 8: Propagated fragment trajectory solutions from 3-independent camera systems denoted by green, red, and blue dots.

4. OWLSS Potential for VPS Testing

Vehicle Protection Systems (VPS) are designed to improve the survivability of ground combat vehicles when targeted by anti-tank guided missiles, rocket propelled grenades, and other small missile threats. There are several VPS systems in development at various stages of maturity [1,9-10]. In general, these systems attempt to detect and engage the incoming threat with another projectile (see Figure 9). Lethal mechanisms include both direct kinetic impact and blast/frag to disrupt or detonate the threat warhead.

Figure 9: An Iron Fist projectile engaging an incoming threat [9].

The resulting engagement can generate both a significant blast wave and a debris field moving both towards and away from the vehicle as shown in Figure 10. A key trade in the development of a VPS concept-of-operations is the optimum distance to engage the incoming threat to ensure survivability of the ground combat vehicle, while limiting collateral damage to dismounted troops that might be accompanying the vehicle. Therefore, understanding the resulting debris field properties as a function of the engagement is an important consideration.

Figure 10: Debris generated in an Iron Fist APS engagement [9].

OWLSS is perfectly suited to help answer these questions. It is a passive, remote system that can be easily reconfigured for dynamic VPS testing without interfering with the engagement space. The VPS engagement measurement volume is much smaller than typically required for arena testing, so fewer cameras per test would be needed. Furthermore, the scenes can be imaged at higher resolution to improve 3D triangulation accuracy and to detect smaller fragments important for assessing human casualties. From a tracking algorithm standpoint, there is nothing inherently different in a dynamic VPS engagement compared to a static warhead detonation. The initial location of the impact or detonation is needed, but OWLSS can derive that by tracking the two projectiles through the endgame. Tracking the projectiles provides the added benefit of an accurate 3D point-of-closest approach measurement for blast/frag APS engagements. Figure 9 illustrates the two projectiles viewed against a white wall for an engagement close to the ground and against the sky in Figure 10. Throughout V&V testing, backdrops have been used as shown in Figure 9 for tracking fragments low to the ground and, as discussed, using sky backgrounds to image larger areas. Because VPS dynamic engagements are between relatively small warheads that can occur many feet above the ground, OWLSS can be configured to detect the full 3D debris distribution exiting the fireball and provide per-fragment correlated kinematic and physical properties to support LVS modeling.

5. Summary

Characterizing warhead fragmentation patterns is ubiquitous across the services. Legacy measurement techniques provide only a sub-set of the data needed to be support LVS modeling. In particular, the de-coupling of mass and velocity measurements with no aerodynamic measurements require analysts to be very cautious with LVS assessments, since the uncertainties of the model inputs cannot be quantified. An increased priority on surgical engagements limiting collateral damage requires a much better understanding and characterization of our weapon systems. The OWLSS system presents a paradigm change in warhead characterization measurement technology. OWLSS is a passive, remote measurement system that can reduce test costs and whose automated algorithms can provide data products in a timelier fashion. Most importantly, OWLSS delivers correlated kinematic and physical characterization on each unique fragment. Better fragment kinetic energy characterization is key to improving LVS modeling. OWLSS has undergone rigorous live-fire testing and systems are transitioning to Government arena ranges for use. The modular nature of the OWLSS technology makes it appropriate to use on a wide range of applications that require fragment tracking. Characterizing VPS engagements and the resulting debris fields fits naturally into this application space.

6. Acknowledgements

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