System of Systems - Survivability, Lethality, Vulnerability Assessment:

Ballistic Vulnerability Modeling Demonstration

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1 Introduction

The Survivability/Lethality Analysis Directorate of the US Army Research Laboratory (ARL-SLAD) is the U.S. Army's primary source of survivability, lethality and vulnerability (SLV) analysis and evaluation support, adding value over the entire system life cycle. ARL-SLAD provides SLV analysis and evaluation support to Army Transformation efforts in order to help develop and acquire a system-of-systems (SoS) that will survive and be highly lethal in all environments against the full spectrum of battlefield threats.

The Army is undergoing transformation both in its command and control doctrine and in the warfighting technologies it employs. This transformation is rooted in the concept of decentralized decision making enabled by advanced network technologies; thus, the Future Force is viewed as a collaborative, adaptive SoS able to quickly dominate the threat across the spectrum of conflict. While traditional item-level survivability/lethality and vulnerability (SLV) methodologies suffice for legacy forces, new methods are needed for the Future Force. The Army Research Laboratory, in collaboration with Physical Sciences Laboratory of New Mexico State University (NMSU), is taking decisive steps to provide an innovative survivability/lethality and vulnerability assessment (SLVA) capability for the SoS (SoS SLVA) by developing the System-of-Systems Survivability Simulation (S4).

2 Background

Leaders enabled by information obtained via networks imply a stronger coupling between disparate components on the future battlefield; consequently, SLVA must consider both individual components *and* how these components relate to the SoS. SLVA must also include multiple leaders who interact over time and space and consume information as they execute their mission, while at the same

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time, responding to Red actions and materiel failures that inevitably occur. Insight into interactions between system components, information flow, and adaptation is the key to the assessment of leader-centric, network-enabled forces.

Via '*agent*-based' modeling (ABM), the S4 is a small-unit force-on-force simulation designed to assess SoS effectiveness [1]. As an ABM, the approach is very different than current Army force-on-force models. In S4, emphasis is placed upon the military decision making processes (DMPs) and the communications network that link these DMPs within a SoS. Each DMP represents a human decision maker on the battlefield that is dynamically driven by the information available during simulation execution.

In FY08, the S4 simulation engine was modified to incorporate ballistic vulnerability data, and the various DMPs enhanced to respond to damage brought about by ballistic interactions. Consequent to these enhancements, we developed new metrics to aid in our analysis of these ballistic interactions. These new metrics, generated by the physics-based vulnerability/lethality (V/L) model MUVES, represent elements of functional degradation (EFD) of individual platforms. EFD are fundamentally different than the loss-of-function metrics used in Army simulation. Functional degradation is determined directly by the damaged components after a ballistic interaction. Via these new metrics, we can assess the impact of ballistic damage upon the System-of-Systems. The purpose of this paper is to describe the S4 ballistic demonstration and highlight the potential benefits of a SoS SLVA to the Test and Evaluation community.

3 SoS SLVA Demonstration Overview

3.1 SoS SLVA PROCESS

System-of-Systems (SOS) is a concept that has emerged recently to account for the ability of communications networks to connect previously autonomous and independent combat platforms across time and space [1]. In this complex battlespace, information is a key element in the survivability of the Future Force [2]. In order to analyze these SOS, one must realize three specific aspects:

1) a physical organization that includes people and materiel,
2) a concept for operations, and
3) a specific mission.

When these aspects are determined we have a SOS for which we can pose proper analytical questions. Figure 1 depicts this notion of a SOS in which the Future Brigade Combat Team (FBCT) as equipped with the 14+1+1 systems [3] as an example of the organization; doctrine is given by FM 3-90.9 [4]; and, the specific mission is described in Section 3.3.

We have established a general process to guide our SOS SLVA analysis efforts as depicted in Figure 2. When beginning an S4 analysis, the initial problem statement is often abstract and suitable questions for experimentation can only be generated with difficulty; however, in interactions with customers, it is crucial to understand the motivations underlying the problem statement so that we can formulate general experimental questions that, when answered, will provide insight to the general problem. We call this problem definition, and represent this activity in Figure 2 step I.

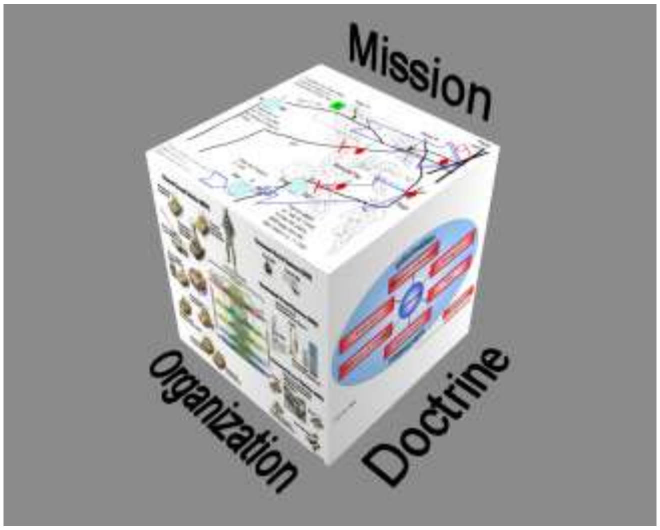

Figure 1 SoS Analytical Model

Once we have a set of experimental questions, we create a concept that defines the set of simulation requirements to provide the data for analysis. This is represented in Figure 2 step II.

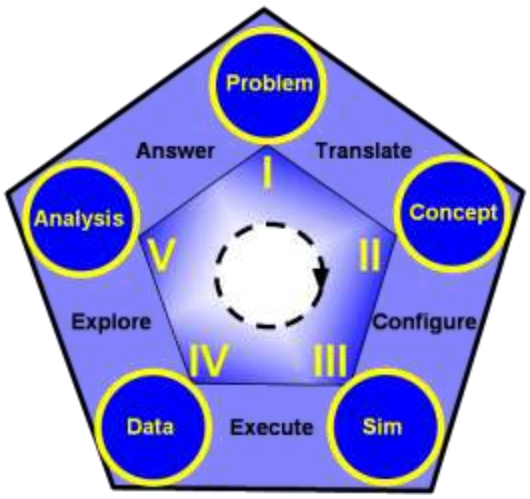

Figure 2 SoS SLVA Process

The concept is then configured into a simulation, which when executed provides the fundamental data for analysis. This is the step from II → III → IV in Figure 2. Between steps IV and V is the data exploration process by which we come to understand and assess results to determine the appropriateness of the simulation to addressing the focus of the study. If it is not, steps II or III are repeated to execute a slightly different version of the simulation. If we are satisfied with the simulation (step V), analysis is conducted to assess the SoS.

3.2 DEMONSTRATION GOALS

The Ballistics & Nuclear/Biological/Chemical (NBC) Division (BND) of SLAD is responsible for development and analysis of ballistic V/L data. To support Army transformation, the BND requires expanded methods to model ballistic effects on entities (personnel, components, subsystems and platforms) and assess the impact on a multi-platform unit's ability to perform a given mission, i.e., to conduct analysis of ballistic interactions in a SoS context.

In collaboration with NMSU, a major goal of this demonstration was to incorporate high resolution ballistic V/L data into S4 and demonstrate the utility of the data to exercise the simulated decision making processes in a meaningful way.

Two modeling methods were chosen for the project study to assess both individual tasks and overall mission success (Figure 3). To support a timely schedule, existing S4 code and platform engineering information was reused as much as possible. V/L data was developed for two platforms; an infantry carrier vehicle (ICV) and an unmanned aerial vehicle (UAV), versus eleven direct fire threats. These data were then applied within the DMP during S4 execution as discussed in Section 5.

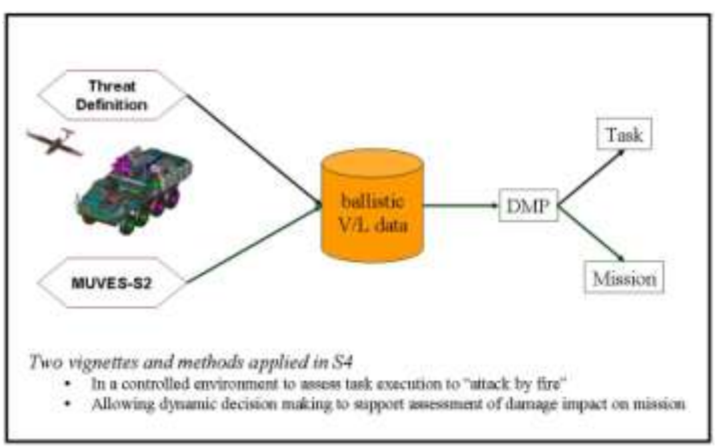

Figure 3 Project Overview

3.3 VIGNETTES AND S4 MODELING METHODS

The vignette chosen for this study was a notional Southwest Asia scenario involving a Stryker brigade combat team. The study focused on two of three platoons of a mechanized infantry company within a task organized combined arms battalion. We included another company in the battalion and some reconnaissance, surveillance and target acquisition pieces to provide sufficient context for our two focus platoons. The Red force consisted of a single tank company using Russian MBTs. Each vignette modeled consisted of two sequential and independent engagements; the first engagement with insurgents armed with rocket propelled grenades (RPG) as the units made their way through a pass and a second engagement with tanks in broken or open terrain. The first engagement created a varied damage state for each platform transiting the pass, with this damage state forming the basis for determining continuation of the mission, and for beginning execution of the second engagement with degraded capability.

As noted in Section 3.2 two modeling methods were applied to these vignettes. The first method limited the scope and control over the simulation to isolate the relationship between *task execution* and lost functionality due to ballistic damage. A single Red tank was scripted with a fixed sequence of way points to simulate shoot and move tactics. Blue scout forces (SF) on the hills were used to provide situational awareness (SA) and an RPG-equipped insurgent threat induced the ballistic damage.

The second method was used to assess *mission success*. Typical of S4 runs, the method allowed the full dynamic nature of the platoon DMP given the mission to provide protection of one platoon by another. The dynamic nature of the DMP for this study is further described in Section 5. As in the previous method, scouts were used to provide SA and an RPG gauntlet induced the ballistic damage. In contrast to the first method, the Red forces were less scripted and a unit of five T-90 tanks was simulated instead of a single tank.

4 Ballistic Vulnerability/Lethality Methodology

4.1 ANALYTICAL FRAMEWORK

For several years, organizations within the Army have collaborated to develop the Missions and Means Framework (MMF) and related tools to support the capabilities identification process within the Joint Capabilities Integration and Development System (JCIDS) [5, 6, 7]. MMF uses a structured approach to describe key elements of military operations in a disciplined, repeatable procedure and to explicitly specify the mission and assess mission accomplishment. MMF requires that a mission be decomposed into the tasks needed to accomplish it. Mission decomposition can begin at any level of war from the strategic national level to the lower tactical level and extend to the lowest level required to address analytical/study objectives and associated questions.

This decomposition can include standard low level tasks to be performed by individual soldiers, platforms or small units. Each task is then analyzed to determine the functions and capabilities that would be required to accomplish the associated purpose, given the conditions imposed by a generic or scenario specific operational environment. The resulting set of required capabilities and functions are then correlated to functions and capabilities provided by the materiel and personnel, (supported by the relevant DOTMLPF [Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities] solutions), that would be required to complete the task. The tasks, with associated materiel and human components, or subsystems, providing specific capabilities, represent the means used to accomplish the Mission, thus the name 'Missions and Means Framework.'

In light of MMF implementation, two analyses for this project were defined to accomplish respective objectives (as noted in Section 3.3): 1) to assess the ability of the unit to execute 'Attack By Fire' task, and 2) to assess the mission to provide protection (one platoon's protection of another). The metrics required for these assessments were fundamentally different than the traditional Loss-of-Function (LoF) values used in current Army modeling and simulation (M&S). To understand the new modeling requirements, the roots of MMF, referred to as the V/L process, must be explained [8, 9].

The MMF-V/L process consists of a series of spaces or levels of information and mappings between those spaces (shown in Figure 4). There are four levels in the MMF-V/L process that represent the states of the threat-on-target interaction. The first level (Level 1) is defined as the set of all possible conditions for threat-on-target interaction. Examples of such information include the velocity at impact due to range from the firer to target, munition impact location and angle, munition type, target type and current condition of target. The mapping from Level 1 to Level 2 ($0_{1,2}$ mapping) relates to the physics of a threat-on-target interaction (i.e., ballistic penetration). The result of the $0_{1,2}$ mapping is then a set of damaged components that is represented by a damage vector at Level 2.

Level 2 is the set of all possible damaged target components such as the perforation of an automatic fire control system or a damaged axle. This is where the methodologies diverge since either the traditional LoF values or MMF metrics can be produced from this level.

MMF-V/L continues to map the damaged components from Level 2 to Level 3

($0_{2,3}$ mapping) by applying system engineering information. The results of this mapping describe how component damage affects the 'functions' of the system (such as mobility, communication, target acquisition, surveillance and firepower).

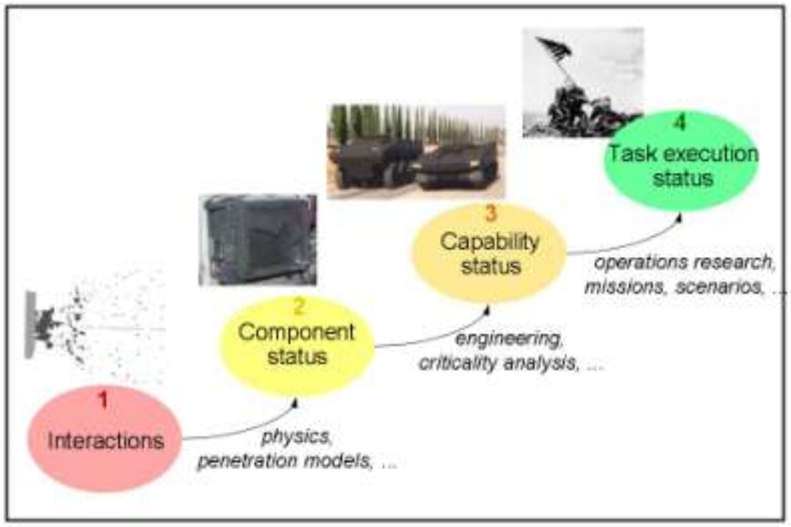

Figure 4 Vulnerability/Lethality Taxonomy

These functions, referred to as 'elements of functional degradation' (EFD), are then grouped to define the 'state' of the system (i.e., a set of EFD).

In contrast, the traditional methodology maps the damaged components (or critical category of components) at Level 2 directly into a combat utility value in Level 4 (an $0_{2,4}$ mapping). Several important distinctions follow between the MMF and LoF metrics [10, 11].

First, LoF values are "estimates of fractional loss of utility." Generally, in combat simulations, these estimates are used as probabilities of no capability. For example, a 0.6 LoF that represents a loss of 60% of system combat utility has traditionally been interpreted as a 60% probability of no capability. There is a profound difference between an estimate of lost fractional utility and a probability of no utility. To substitute the latter for the former is fundamentally incorrect.

Second, a panel of weapon system experts, who must "mentally integrate" over all possible combat missions, weather, terrain, and other appropriate parameters, derives the LoF estimates of fractional utility. Therefore, averaging for scenario-specific criteria is done early in the analytical process. In models such as CASTFOREM, these averages are applied to all possible combat scenarios. Because averaging is performed early in the analytical process, it is impossible to derive scenario-specific LoF values from the traditional methodology. In contrast, MMF provides a baseline of engineered functional performance independent of scenarios, thus allowing the user to define the variations.

Third, the traditional methodology produces essentially two metrics, mobility (M) LoF and firepower (F) LoF. The probability of catastrophic (K) kill is also produced; however, it is recorded separately, is a true probability, and is also included with the M and F metrics. Some model applications de-aggregate the M or F LoFs and K probabilities to produce 'M-only,' 'F-only,' and 'K-only' values for use. However, this practice may produce inaccurate values and should be avoided. In contrast, MMF metrics provide the mutually exclusive probabilities that a SoSA requires.

Fourth, traditional LoF metrics cannot be directly validated through testing. It is impossible to conduct an experiment to produce a LoF value that could then be compared to an analytical result. This is in contrast to the Level 3 MMF-EFD that can be validated directly through experimentation. For example, it is possible to conduct an experiment by firing at a combat vehicle and then evaluate its performance by driving it on a test track or acquiring and engaging targets on a gunnery range. Experienced engineers and analysts can then make assessments of the vehicle's remaining functional capability.

4.2 V/L MODELING

MUVES-S2 is an analytical model developed by ARL for V/L analyses of ballistic damage mechanisms against air and ground mobile military targets [12]. MUVES-S2 is the Army's primary model for V/L data development supporting system acquisition. For this project, V/L data was generated for an ICV and an UAV via MUVES-S2.

As previously mentioned, MMF-EFD are essential to SoSA. Table 1 shows the MMF-EFD defined for the ICV in this study. Boolean expressions, often referred to as *fault trees*, are used to model the MMF-EFD in MUVES-S2. A graphical representation of a fault tree is shown in Figure 5.

Mobility	Firepower
m1.1 Reduced Maximum Speed 0-20%	f_1 Lost Ability To Fire Buttoned Up Main (RWS)
m1.2 Reduced Maximum Speed 20-40%	f_3 Degraded Initial Rate of Fire of Main (RWS)
m1.3 Reduced Maximum Speed 40-60%	f_4 Degraded Subsequent Rate of Fire of Main (RWS)
m1.4 Reduced Maximum Speed 60-80%	f_7 Total Loss of Firepower Main
m1.5 Reduced Maximum Speed 80-100%	f_{12} Total Loss of Firepower Secondary
m2.1.1 Reduced Acceleration 0-20%	
m2.1.2 Reduced Acceleration 20-40%	**Communication**
m2.1.3 Reduced Acceleration 40-60%	$x_{1.1}$ Reduced Range (antenna loss)
m2.1.4 Reduced Acceleration 60-80%	$x_{1.2}$ Reduced Range (power amp loss)
m2.1.5 Reduced Acceleration 80-100%	x_2 Lost Line-of-Sight (LOS) Data
m2.2.1 Reduced Steering 0-20%	x_3 Lost LOS Voice
m2.2.2 Reduced Steering 20-40%	x_4 Lost Non-LOS Data
m2.2.3 Reduced Steering 40-60%	x_7 Lost External Communications
m2.2.4 Reduced Steering 60-80%	$x_{7.1}$ Lost Encryption Capability
m2.2.5 Reduced Steering 80-100%	$x_{7.2}$ Lost Channel/Frequency Selection Capability
m2.3.1 Reduced Braking 0-20%	
m2.3.2 Reduced Braking 20-40%	**Target Acquisition**
m2.3.3 Reduced Braking 40-60%	a_1 Lost Daylight Acquisition
m2.3.4 Reduced Braking 60-80%	a_2 Lost Night Acquisition
m2.3.5 Reduced Braking 80-100%	a_3 Lost Range Finder Capability
m2.4 Reduced Visibility (driver's sensor)	
m3.1 Stop After 30-60 Minutes	
m3.2 Stop After 10-30 Minutes	
m3.3 Stop After 1-10 Minutes	
m3.4 Stop After 0-1 Minute	

Table 1 Infantry Carrier Vehicle MMF-EFD

The expressions are built up by using ANDs and ORs to join together names of subsystems and components. It expresses the nature of the dependence of some functionality on the condition of those subsystems and components.

The fault tree in this example represents the internal communications function and may be viewed as a road network between two terminal nodes. From this perspective, if any of the subsystems or components is nonfunctional, it is deleted, which at least partially severs the network. The fault tree expresses the assertion that the corresponding functionality is available exactly when the network retains at least one path that connects the two terminal nodes. Each of the subsystems in a fault tree may, in general, have its own expansion as a separate fault tree.

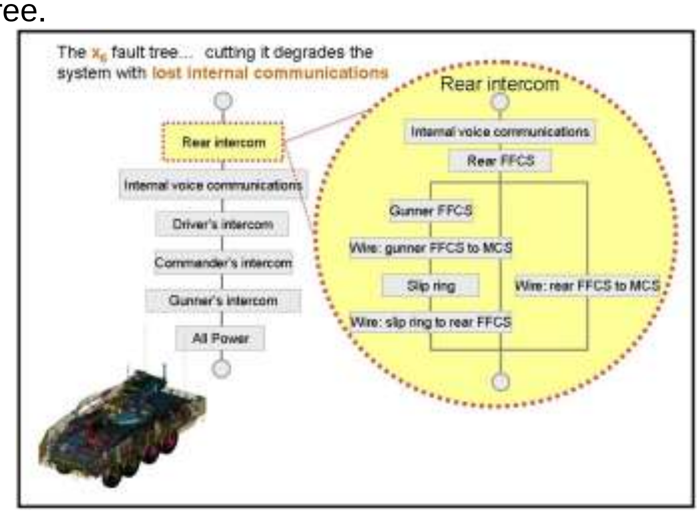

Figure 5 Platform Modeled Representation

4.3 DATA ANALYSIS AND PROGRESSION

Figure 6 shows the progression of data analysis. Data analysis typically begins at the platform level to understand the vulnerabilities associated with specific threats and engagement parameters. For this study, both the traditional LoF and MMF-EFD were first analyzed at the platform level as output by MUVES-S2. The limitation of this type of analysis is that it is at a *static* point in time with no accumulation of damage for multiple hits (or engagements). With S4, the analysts were now able to analyze data *dynamically* over time during execution of a vignette.

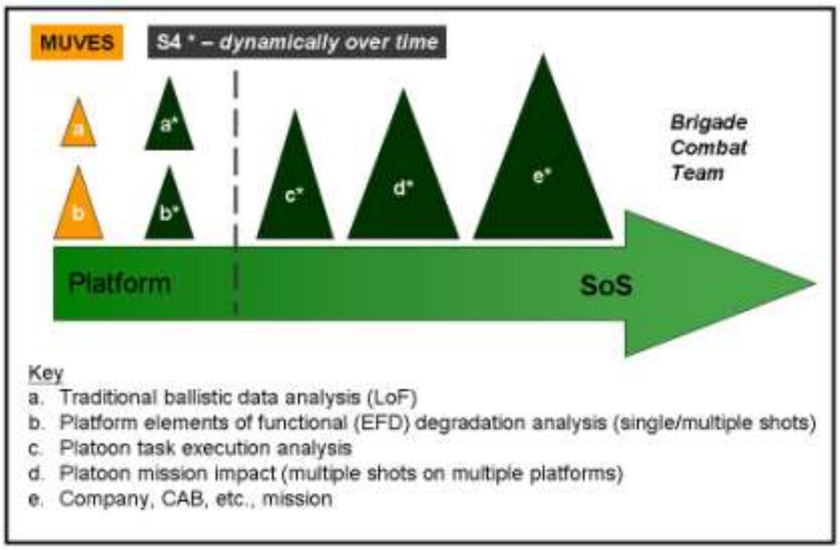

Figure 6 Data Analysis Progression

The focus of the analysis then shifted from platform to platoon level while examining both task execution and the impact of multiple engagements on mission completion. Although the demonstration limited the scope to platoon level, the goal is to extend the analytical capability to a level of a Brigade Combat Team (BCT).

5 Decision Making Processes (DMP)

As an ABM, S4 uses subsystem degradations (SSD) to model the affects of LoF and MMF-EFD (example in Table 2) within the DMP defined in the simulation. The minimum and maximum delays (in seconds) for an *agent* to identify the SSD once it has attempted to use the affected subsystem.

EFD	Description	Degradation Type	Parameter	Min Delay	Max Delay
m2.3.1	Reduced braking capability by 20%	ReducedBraking	0.2	30	60
m2.3.2	Reduced braking capability by 40%	ReducedBraking	0.4	20	30
m2.3.3	Reduced braking capability by 60%	ReducedBraking	0.6	15	25
m2.3.4	Reduced braking capability by 80%	ReducedBraking	0.8	10	20
m2.3.5	Reduced braking capability by 100%	ReducedBraking	1	5	10
m3.1	Stop after 60 minutes	StopAfterTMinutes	60	20	25
m3.2	Stop after 30 minutes	StopAfterTMinutes	30	15	20
m3.3	Stop after 10 minutes	StopAfterTMinutes	10	10	15
m3.4	Stop after 1 minutes	StopAfterTMinutes	1	5	10

Table 2 Subsystem Degradation (SDD)

Platform crew is not necessarily instantly aware of what damage the vehicle has sustained after a ballistic engagement. It can take time to diagnose a system malfunction to the point where an accurate assessment may be communicated to a commander. Additionally, ignorance of damage to self is a realistic source of errors in tactical decision making. As such, information about damage is simulated in two steps:

1) When damage is sustained, the DMP is immediately notified that there is a problem with the affected subsystems, but the details of the problem are not yet communicated.

2) Discovery of the exact SSD is delayed. In S4, all valid SSD are mapped to either a set of subsystems or the platform as a whole. For subsystems the SSD is revealed to the *agent N* seconds after the first use of the subsystem, where N is a uniform random variable such that: T1 <= N <= T2. Platforms are handled similarly to subsystems, but there is no requirement for first use. The *agent* is notified of the SSD *N* seconds after the damage was sustained.

For example, a platform may be ambushed and hit with a munition that causes m2.3.1 as defined in Table 2. Immediately after the hit, the platform *agent* is informed that something is wrong with the mobility subsystem. If the platform had already been on the move, constituting first use, the *agent* is informed 30-60 seconds later that the problem is a 20% reduction in braking ability. This delay corresponds to the amount of time an operator would spend diagnosing the problem.

Damage is communicated via 'situation reports' in S4. SSD appear in the report in addition to other attributes such as position. These reports are triggered when something has changed in the simulation. Reports propagate up through the team hierarchy to the commanding echelon and then are disseminated back down through the entire force. Reports of immobile platforms, or loss of firepower can influence a platoon leader or company commanders assessment of combat power, and alter the way that leader perceives and responds to particular simulation situations. Platforms, aside from platoon leader or company commander, do not receive communication of other platform damage such as EFD. The only information communicated is that a platform is ALIVE or DEAD.

6 Benefits to the Test and Evaluation community

To support Army Transformation, the Army Test and Evaluation Command (ATEC) is also developing new processes and products within their Mission-based Test and Evaluation (MBT&E) strategy (Figure 7) [13]. MBT&E can be viewed as a subset of MMF, requiring mission decomposition and systems engineering information.

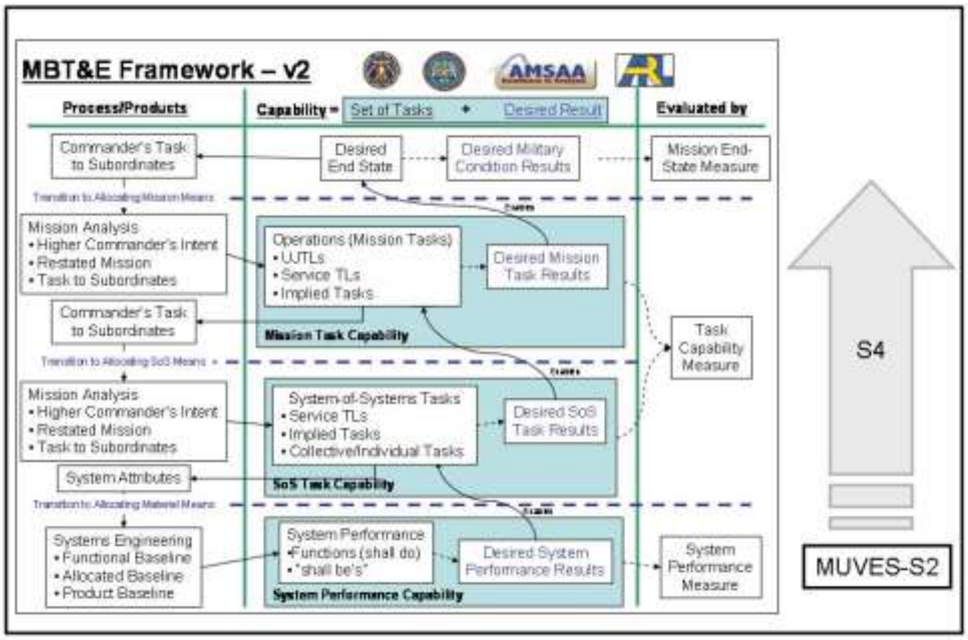

Figure 7 Mission-based Test and Evaluation

Much of the data analysis for the SoSA, as described in Section 4.3, is applicable to the MBT&E processes. Platform EFD defined for V/L analysis are comparable to the systems engineering functional baseline as noted in the bottom left-hand side of Figure 7. Quantifying the EFD in the testing community would benefit both ARL and ATEC in support of SoS evaluation. Use of the EFD in S4 supports the MBT&E by exploring the impact of ballistic interaction and mission end-state results. For example, S4 can help reveal what EFD have impact on task execution or mission completion thus help focus T&E planning. This capability is particularly helpful in determining recommended vulnerability reduction measures in the vehicle design process. Understanding how particular EFD affect mission outcome enables the analysts to identify subsystem vulnerabilities that have the largest impact on mission accomplishment, and therefore prioritize vulnerability reduction measures based on maximum impact to the warfighter.

7 Summary

In summary, system survivability is expanding from armor protection toward network centric cooperation. New methods are under development to analyze survivability within this paradigm. The ARL, in collaboration with NMSU, is taking decisive steps to provide an innovative survivability/lethality and vulnerability assessment (SLVA) capability for the SoS (SoS SLVA) by developing the System-of-Systems Survivability Simulation (S4).

In FY08, the S4 simulation engine was modified to incorporate ballistic vulnerability data, and the various DMPs enhanced to respond to damage brought about by ballistic interactions. Consequent to these enhancements, new metrics were developed to aid in analysis of these ballistic interactions that are fundamentally different than the traditional metrics used in current Army models and simulations. Instead of LoF, the DMP in S4 utilized additional information provided by EFD. For small test cases, the utility of EFD in the simulated DMP has been demonstrated to show a relationship between EFD and execution of a task or mission.

S4 breaks new ground for addressing SoS survivability, lethality, and vulnerability analysis. Emphasis in S4 is given to decision making and system performance. The ballistic demonstration, using S4, enhances the analytical ability to examine relationships between materiel and battlefield metrics such as situational awareness and situational understanding. Further planning and development of S4 is needed to mature the methods necessary to fully support Army studies. Metrics defined within these new methods should be verified by testing and applied to system evaluation. With close collaboration between communities these new methods will close analytical gaps and enable the evaluation of SoS survivability.

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