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The Mathematical Structure of the Vulnerability Spaces

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The vulnerability/lethality (VL) process structure is an attempt to bring mathematical formalism to VL analysis and place it on a more scientific foundation. A key point of the mathematics in the process structure is the basis it will provide for future work. This report will develop the mathematics of the VL process structure and present applications which demonstrate the utility of this mathematical formalism in solving some classical VL analysis problems.

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TABLE OF CONTENTS

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1. INTRODUCTION

In a previous report, Klopcic, Starks, and Walbert (1992) developed the process structure, or taxonomy, for vulnerability/lethality (VL) analysis. More recently, Walbert, Roach, and Burdeshaw (1993) have refined this process and extended its application to areas outside the realm of VL analysis (Roach 1993). This process structure is an attempt to bring mathematical formalism to VL analysis, to make the process appear less of a black art and place it on a more scientific foundation. A key point of the mathematics in the process structure is the basis it will provide for future work. The observation that VL analysis can be thought of as a series of mappings between spaces at various levels or stages of the process was first made by Deitz and Ozolins (1989). The use of the terms spaces and mappings was without any connection to the mathematical formalism associated with them. This report will develop the mathematics of the VL process structure, demonstrating that at each level, one can, in fact, define closed, metrizable vector spaces. There are, in general, many metrics which can be defined on a given metric space. In this paper, one metric is presented, and several examples of its use are illustrated. It is not claimed that this metric is the best or the most appropriate one; the purpose here is simply to show that such metrics exist and how they might be used. It will also be shown that the metrics defined on each of the spaces impose a suitable topology so that the mappings between the spaces can be made continuous. Finally, applications will be considered which demonstrate the utility of this mathematical formalism in solving some classical VL analysis problems.

2. BACKGROUND

We begin with a review of the VL process structure, in the context of classical vulnerability analysis. VL analysis is the process of determining the effectiveness of a given weapon (the threat) on a combat system (the target). There are two parts to this process: determining the effect of the threat on the capability of the target, and determining the combat significance of the reduced target capability. Beginning with the first instant of influence of the threat on the target, the target passes through a series of damage conditions leading to a final state of (possibly) degraded capability. Empirically, these stages of degradation are monitored at three points: 1) the initial conditions at first instant of threat/target interaction; 2) the level of damage done to the target when all primary (if not secondary) influence of the threat is complete; and 3) the remaining capabilities of the target (such as speed, accuracy, etc.) after all threat influence is complete. One can postulate the existence of mappings from the first stage to the second, and from the second stage to the third. The first part of the classical VL analysis problem is to model the concatenated mappings for a given threat/target combination to determine the effects of the threat on the target.

The basic assumptions and definitions given in Klopcic, Starks, and Walbert (1992) are:

Assumption 1) There are three levels of information making up the VL analysis universe; these levels represent the state of the threat/target system at three (possibly overlapping) time intervals. Spaces can be defined at each of these levels.

Assumption 2) The physically realizable points in each of the spaces are observable and/or measurable.

Assumption 3) The points in each space are vectors, consisting of one or more elements.

Assumption 4) Mappings exist from each level to the next, and from a space at each level to a corresponding space at the next level.

Under these assumptions, one can write:

Definition 1:
1) VL Space 1, or VL1, is the set of all possible initial conditions for target/munition interaction.
2) VL Space 2, or VL2, is the set of all possible target component damage vectors.
3) VL Space 3, or VL3, is the set of all possible system capability degradation vectors.

Definition 2: The dimension of a space is the number of elements in a vector (point) in that space.

Definition 3: The cardinality of a space is the number of vectors (points) in that space.

Definition 4: The mapping from VL1 to VL2 is denoted by O12; similarly, the mapping from VL2 to VL3 is denoted by O23.

(We note that the current work will demonstrate the mathematical propriety of the terms "vector" and "space.")

In the more traditional VL analyses, one proceeds beyond level 3 to measures of effectiveness (MOEs), such as mobility kill or firepower kill. These MOEs will be said to be at level 4, and, since level 4 represents quantities which are neither measurable nor observable, no attempt will be made here to impose any mathematical structure on it. Moreover, since any attempt to infer combat utility by going from level 3 to level 4 requires the introduction of terrain features, scenario, doctrine and tactics, such work is beyond the scope of the traditional VL analyst. There is, however, a considerable effort underway within the vulnerability community to help develop the mappings from level 3 to level 4 in a manner which satisfies user requirements and uses newer and analytically more powerful metrics.

As a direct result of the inability of lumped-parameter and point-burst type deterministic vulnerability models to describe adequately the results of live fire tests on the Bradley Fighting Vehicle and the Abrams Tank, the Ballistic Research Laboratory (BRL) developed a stochastic methodology within the point-burst modeling framework (Deitz and Ozolins 1989) to enable the analytical process to begin to account for the numerous variabilities inherent in the physical processes during threat/target interaction, as well as in the collection and interpretation of damage data. Such variabilities include nonhomogeneities in armors and their resulting erosion and/or fracture properties, differences in target components or locations from those depicted in the computer description, operating conditions (resulting in different leakage rates of fluids from broken hoses or tanks), measurement errors, and numerous others, known and unknown. The introduction of stochastic modeling concepts has provided the VL analyst with the means for estimating the likelihood of occurrence of a particular live fire event, assuming the constitutive elements for the formulation of the mappings O12 and O23 are known. In effect, conducting numerous repetitions of the same live fire shot in the computer, using assumed or measured distributions for the above variabilities, generates a distribution of resulting damage and/or remaining capability. The result of a particular test event may then be compared with its expected distribution as inferred from the modeling process. The ultimate goal is to use the analytical models to replace most, if not all, of the costly live fire tests.

One of the greatest difficulties in this process (aside from the problems of determining distributions for the operant variabilities and determining whether a particular test event "belongs to" a given distribution of outcomes) is in determining the constitutive elements of the O12 and O23 mappings. On a fundamental level, O12 deals with physics, and O23 deals with engineering; that is, O12 describes how the threat causes damage to the target, and O23 describes how that damage degrades the capabilities of the target. There may be a definite, observable synergism between damage mechanisms (blast and fragment impact, for example) which precludes treating them as independent. The same is true of the capability degradation process, determined by the synergism among target system components (e.g., a shorted wire in a mobility-related component causes a power supply to burn out, resulting in a firepower loss).

As an example of the O23 mapping process, the Degraded States Vulnerability Methodology (DSVM) (Starks 1991; Abell, Roach, and Starks 1989) for an armored fighting vehicle can describe the vehicle's performance degradation in terms of a six-element vector (Mobility, Firepower, Acquisition, Crew, Communications, Ammunition). Each of these elements is termed a capability category, and each capability category is represented by a capability level which defines a particular performance degradation (i.e., reduced speed, reduced accuracy, etc.). Included within a capability category are levels representing all possible combinations of degradation that could occur simultaneously, as well as a "no degradation" level. These two properties of the capability category make the levels within a category both mutually exclusive and exhaustive. This point will be quite significant in what follows. For any set of components, one, and only one, capability level will be achieved within each capability category. This combination of six capability levels, one from each category, represents the degraded state of the vehicle. Obviously, one is not restricted to six capability categories; the number depends on the combat system and its required capabilities. Moreover, there is no methodological restriction to discrete levels within each category; the levels could form a continuum. This methodology provides a more robust set of measures when compared to the traditional Damage Assessment List (DAL) measures which provide only a single loss of function (LOF) value for both mobility and firepower. In the terminology of the process structure, the DAL measures are a mapping from level 2 directly to level 4, without regard to the intermediate level. Starks (1991) has shown the dangers inherent in skipping over levels.

3. THE VULNERABILITY SPACES AS VECTOR SPACES

This section will show that it is possible to define vector spaces, in the formal mathematical sense, at levels 1–3 of the VL process structure. It will be seen that there could be a number of different vector spaces defined at each level for a particular VL problem, and that the vector spaces at each level will differ from one VL problem to another. To this end, some preliminary discussion will be useful.

The goal of introducing formalism into the VL process structure is to apply the mathematics to the solution of a variety of problems and develop new VL measures more consistent with current modeling and analysis requirements. While a great deal of information is required to conduct a VL analysis, such as geometric target descriptions, it is certainly not reasonable to attempt to include everything in a vector space. We therefore chose to consider the vector spaces "in the context" of a particular problem or class of problems. For example, if we are interested in problems concerning kinetic energy projectiles against tanks, then target geometry, penetrator (nonkinematic) characteristics, and a wealth of other information comprises the context of the problem. The point is, without the "context," a particular vector space which we define is not likely to characterize the problem uniquely; there is no reason why it should.

It might be appropriate to consider an analogous example. In the simple mass-spring system with damping, given by

$$mx'' + cx' + kx = 0, \text{ with } x'(0) = A \text{ and } x(0) = B,$$

where ′ denotes differentiation, we could consider two spaces and a mapping from one space to the other as follows. Let level 1 consist of 5-tuples of the form

$$\{m,c,k,A,B\}.$$

Now, these 5-tuples of real numbers do not specify, uniquely, any physical problem unless we are given the context: mass spring system as above. The governing differential equation itself is a mapping which takes the points at level 1 and maps them into points (solutions) at level 2. If the solution to the differential equation is written as

$$x(t) = C * \exp(-bt) * \sin(ut + d),$$

then points (4-tuples) at level 2 are given by

$$\{C,b,u,d\}.$$

Again, in the context of the problem (the form of the solution of the given class of differential equations), the four numbers which comprise the elements of the 4-tuple at level 2 are sufficient to describe that solution. It should be fairly evident to the reader that one could define vector spaces at each level from these n-tuples of numbers. These vector spaces do not contain all the information necessary to solve the problems (absent are such things as the rules of algebra and differential calculus), but the information is nevertheless sufficient to answer questions such as "How close is one mass-spring system to another?" or, "How close is one solution of the differential equation to another?"

Returning to the VL analysis problem, the threat/target combination may be thought of as a system, and the process of threat/target interaction as states through which the system passes. These states are time-varying, and the process is stochastic. It is thus seen as important to have time as an element of each point at each level. More will be said about this shortly, but for now, let T1, T2, and T3 denote the times at which information is being considered at levels 1, 2, and 3, respectively. We begin with a discussion of what the points at each level might look like. In particular, suppose we are concerned with a kinetic energy threat against a specific target. Let the threat spacial coordinates be x,y,z, and let the target spacial coordinates be u,v,w. If $'$ denotes differentiation with respect to time t, then a point at level 1, for example, might be given by

$$(x,y,z,x',y',z',x'',y'',z'',u,v,w,u',v',w',u'',v'',w'',T1).$$

The coordinates u,v,w refer to a fixed point on the target to which the target geometry is referenced. The threat coordinates may themselves be arrays referring to the various damage mechanisms from the threat; the same may be true of the target coordinates if the target is an array of equipment.

The number and type of primary damage mechanisms produced by the threat and the number and type of target(s) determine the form of the elements of VL1. A primary damage mechanism is one which is a property of the threat at time T1. For example, the kinetic energy of a penetrator or fragments is a primary mechanism, as is blast. Fire is not a primary damage mechanism by this definition, unless, of course, the threat is a flame weapon. If the threat produces a set of, say, k fragments, then the x, y, and z elements above are themselves arrays like

$$x = \{x1,x2,x3,...,xk\}$$

$$y = \{y1,y2,y3,...,yk\}$$

$$z = \{z1,z2,z3,...,zk\},$$

as are the corresponding velocities and accelerations. If blast is a primary damage mechanism, then elements of the corresponding points in VL1 also contain the position coordinates of a (specified) point or points on the blast wave. These examples illustrate clearly the need for specifying the time T1, since it is highly unlikely that all k fragments and the blast from a fragmentation munition would arrive at a point of influence on the target simultaneously. It should also be noted that the "target" may be in several locations, as is the case of considering a howitzer together with its resupply vehicle, or all howitzers in a battery. For simplicity in the current exposition, it suffices to assume the threat to be but a single, nonfragmenting object possessing kinetic energy as its only damage mechanism, and the target to be a single item. In general, any property of the threat/target system which can be described by a number or a set of numbers (i.e., quantified) could be included in the elements of points in VL1.

For a given threat/target combination, the desired level of detail for conducting a particular VL analysis dictates such parameters as the number and size of the components included in the geometric target description and how these components are to be grouped, or lumped, together. In the lumped-parameter Compartment Model (Nail, Beardon, and Jackson 1979), for example, all components in the engine compartment are treated as one generalized component, the same size as the entire compartment. A more detailed point-burst model may contain all fuel and oil lines, electrical wires, and detail at that level in a precise geometric description. Once the desired level of detail is determined, the n-tuples in VL2 consist of real numbers, the values of which represent a level of dysfunction of these components in all possible post-shot states at the chosen time T2. For example, if the component is a hydraulic line with a hole in it, the element of the n-tuple corresponding to the hydraulic line might be the ratio of the fluid pressure capacity of the damaged line to the original capacity. Thus, if the levels of dysfunction of a target's k components are denoted by c1, c2, ..., then a point in VL2 might look like

(c1,c2,c3,...,ck,T2).

VL3 is concerned with target capability, so that, in this case, the points are n-tuples of values of subsystem capabilities or functions, such as speed or main gun accuracy. The DSVM, described earlier, might map the points in VL2 into points which might look like

(Level of ability to Move, Level of ability to Function,
Level of ability to Communicate, T3.)

For example, if one subsystem capability is top speed, and the target system is measured as having only 30% of its pre-shot capability, then the element in the VL3 n-tuple corresponding to top speed is 0.3. Note that this value has an implicit dependence on the pre-shot capability of the target; the elements of the n-tuples in VL3 are measurable quantities. It is also important to note that these pre- and post-shot capabilities imply measurement against a standard–in this case, a speed standard. Such standards do not relate to any particular mission profile or battlefield condition to which the target may be subject. Rather, the standards are based on inherent expectations for the target, such as a top speed of x Km/hr on a paved level road. In this way, VL3 is kept independent of the notion of battlefield utility, wherein one would ask whether a 70% reduction in mobility has any effect on the ability of the target to carry out a particular mission. This is the distinction between levels 1–3 and level 4. Analytically, if one were to evaluate the elements, or capability categories, of vectors in VL3 at any time prior to T1, these capabilities would be the baseline, or pre-shot, capabilities of the target.

In the context of mathematical vector spaces, it will be important to consider the independence of the elements of each n-tuple at each level. While the examples given for level 1 and level 2 have rather obviously independent elements, it is less obvious that the elements (or capability categories) at level 3 are independent of one another. Indeed, some component capabilities may be represented more than once in VL3, as implicit parts of several subsystem capabilities. For example, a battery might be a part of the ability to communicate as well as to move. This fact does not affect the independence of movement and communication, however. The test is whether one must be able to move in order to be able to communicate. While it has been stated that the capability levels within each category of a DSVM analysis can be made mutually exclusive and exhaustive, it is a more difficult problem to ensure that the categories themselves cover all requisite system capabilities in a mutually exclusive (mutually independent) manner. For the purpose of this discussion, we will assume the elements of the VL3 n-tuples to satisfy these criteria.

Note also that the choices of the times T1, T2, and T3 are somewhat arbitrary. For example, in most cases, T1 would be taken as the instant of "initial" influence of the threat on the target. But in the case of a fuel-air explosive munition, it may be more desirable to use, as T1, that instant when peak cloud pressure is reached. T2 is generally chosen as that first time after which all elements of the damage mechanism coordinates x,y,z have zero velocity. While such choice of T2 is relatively simple in a computer simulation, safety and other concerns usually dictate that empirical choices of T2 occur somewhat later than this. Moreover, since the process of damage assessment is not accomplished instantaneously, the empirical value of T2 is really an interval. Similarly, T3 might be chosen as that time when all secondary influence of the threat has ceased; that is, all leaks induced by the threat munition have stopped, as have similar secondary effects. Of course, some of the effects may not appear until the target system is "exercised," and some may be aggravated by exercising the target, so that, just as for T2, the empirical value of T3 is really a time interval, during which the target state continues to vary. This time "smearing" is one factor which may impede comparison of empirical data with model output; it may be considered as measurement error.

The choice of the value of the dimension n for each of the three VL sets for a particular VL analysis problem clearly depends on the threat and target complexity and the desired/required level of accuracy of the analysis. It must also be noted that the complexity of the VL analysis problem grows exponentially with the value of n, as will be seen shortly. As the points in VL1, VL2, and VL3 have been defined, they are n-tuples (where n may be different at each level) of real numbers and, as such, look like vectors in standard Cartesian n-space. We will exploit this fact in what follows.

A bit more background discussion is necessary before stating and proving the main result of this section. In particular, it is clear that we will need to include in the spaces at each level such entities as "zero vectors," "additive inverses" (e.g., vectors, the elements of which are negative numbers), and notions of addition, subtraction, and scalar multiplication. Perhaps surprisingly, most, if not all, of these requisite features are present, in a physically realizable sense, in the VL process structure and its extensions.

Since the vectors representing "all damage mechanisms are at the origin of coordinates, with zero velocity and acceleration at time t=0," "all components have zero dysfunction," and "all subsystems have zero capability loss" are clearly members of the sets VL1, VL2, and VL3, respectively, then the sets VL1, VL2, and VL3 contain the zero vectors. That is, each VL set contains a vector each element of which is zero. Addition and subtraction of the elements within each of the VL sets may be defined in the usual way:

$$(x,y,z) + (u,v,w) = ((x+u),(y+v),(z+w))$$

and

$$(x,y,z) - (u,v,w) = ((x-u),(y-v),(z-w)),$$

for example. No attempt will be made here to attach meaning to the sum of two vectors at any level; it will be important to do so in the development of new metrics, especially at level 3, however (see, for example, Walbert and Roach [to be published]).

An important question to ask is whether the sum of two vectors in one of the VL sets is a vector in that VL set (the property of closure under addition). An equally important question is what is meant by the quantity (x-u), above, if x-u < 0, in any of the VL spaces, or by (x+u) if (x+u) > 1, in VL2 or VL3. The goal, clearly, is to establish the VL sets as proper vector subspaces of their respective Cartesian spaces, allowing VL analysis to take advantage of the power of vector-space mathematics. In VL1, negative position coordinates pose no problem; velocities might be negative relative to some frame of reference for the problem other than the threat or the target; negative accelerations might represent a threat which is slowing down relative to the target. Time zero is entirely arbitrary and might be chosen, for a particular problem, to be four days after the threat impacts the target, so the time elements in VL1, VL2, and VL3 would all be negative. The least obvious explanations are for dysfunction values at level 2, which are greater than 100% or less than zero, and at level 3, for capability levels greater than 100% or less than zero.

There are several ways to view this problem. One could simply introduce the vectors whose elements are negative numbers as an artifice to achieve the end goal and allow the O2,3 mapping to treat dysfunction values less than zero as zero, and dysfunction numbers greater than 100% as 100%. Similarly, an O3,4 mapping could consider capability values less than zero as zero and capability values greater than 100% as 100%. This is a very simple and straightforward, though somewhat artificial, way to resolve the dilemma. There is ample precedence for such solutions, with rather powerful consequences. The most obvious example is the development of complex numbers to provide solutions to relatively simple algebraic equations such as (x**2) + 1 = 0.

Another way to view the problem, and one which is considerably more satisfying from a vulnerability analyst's point of view, is provided by the Battle Damage Repair (BDR) Methodology developed by Roach (1993). First, consider the n-tuples in VL2, the elements of which are negative numbers, to represent "repair strategies." That is, these n-tuples represent levels of functionality which can be restored to the set of dysfunctional components by repairing or replacing the damaged parts. Similarly, in VL3, the n-tuples with negative elements are the images, under the O2,3 mapping, of the repair strategies in VL2. They represent those capabilities which can be restored via certain repair strategies. It remains to consider the significance of dysfunction values or capability values greater than 100%. These n-tuples are also significant in terms of BDR. In particular, take an example in VL2 of a hydraulic line, and suppose one wished to sum the two vectors in VL2 with elements 0.5 and 0.75 corresponding to two possible states of damage to the hydraulic line. (In this case, we have normalized the dysfunction values to the range [-1,1].) This sum might be taken to look at the result of two shots against the line, or of two fragments from the same shot impacting the line. The sum vector would have a value of 1.25, a number clearly not physically realizable (measurable and/or observable) in this case. (In truth of fact, the number 0.95 should cause just as much concern for the hydraulic line as a number like 1.25, since a line which is 95% dysfunctional is unlikely to be supporting sufficient fluid pressure to perform its function. That is, 0.95 may also be physically unrealizable in the sense that such a component capability level is virtually indistinguishable from a total loss of capability.) In any event, the dysfunction value of 1.25, under the BDR methodology, represents a hydraulic line which requires more repair than one with a dysfunction value of 1.0. For example, a single hole (dysfunction value 0.75 or 0.50) might be repairable by one patch requiring 60 min total repair time. Two holes (dysfunction value 1.25) might require 75 min (25% more) repair time (the repair kit is on site, and the hydraulic line is exposed for repair, so repairing the second hole doesn't double the time required to repair the first hole). Thus, a component exhibiting greater than 100% dysfunction is simply considered to be completely nonfunctioning; the O2,3 operator will map such component dysfunction values into points in the capability space reflecting the fact that more than one simple repair is required to restore full capability. (The author is indebted to Dr. Michael W. Starks, who first suggested this in a private communication.)

The manner in which the n-tuples have been defined makes interpretation of scalar multiplication quite straightforward (double all damage, halve all capability, for example).

Finally, we reproduce here the formal definitions of vectors and vector spaces (see Greenberg 1978, for example):

Definition 1: A vector is a directed magnitude.

Definition 2: A set V of vectors is a (linear) vector space if the following are true.

1) Addition (denoted by +) is defined between any two vectors in V such that if x and y are in V, so is x + y. (V is said to be closed under addition.) Also, x + y = y + x (addition is commutative), and (x + y) + z = x + (y + z) (addition is associative).

2) V contains a vector O (the zero vector) such that x + O = x, for each x in V.

3) For each x in V, there is a vector -x such that x + (-x) = O.

4) Scalar multiplication is defined between any vector in V and any scalar such that if x is in V and A is any scalar, then Ax is in V. (V is closed under scalar multiplication.) Also,

$$A(Bx) = (AB)x$$
$$(A + B)x = Ax + Bx$$
$$A(x + y) = Ax + Ay$$
$$1x = x, \text{ and}$$
$$0x = 0.$$

With this background information, it is now possible to state and prove the main result of this section:

Theorem: Vector spaces can be defined at each level of the VL process structure.

Proof: The basic elements of the proof have been given in the foregoing discussion. First, since the n-tuples of real numbers which are the points at each level are clearly points in Cartesian n-space, they can certainly be considered as vectors. Addition of two vectors has been defined, and significance has been given to vectors with element values outside the usual range, so that closure under addition is satisfied. It is well known that element-wise addition is commutative and associative, so condition 1) of definition 2 is satisfied. We have shown that zero vectors exist, so condition 2) of definition 2 is satisfied. The notion of repair strategies provides the additive inverses to satisfy condition 3) of definition 2. Finally, the requirements for scalar multiplication are trivially satisfied, so we conclude the theorem to be true.

It should be noted that while varying degrees of component dysfunction are easily imagined, so that any vector in a space at level 2 is "reasonable," it could very well be true that no conventional threat weapon could cause a particular damage vector. For example, a component buried inside a number of other components could not possibly be the only component "damaged" by fragments; the fragments couldn't reach it without damaging other components along the way. That buried component could, however, suffer a dysfunction due to a reliability failure. Hence, in the broader context of extensions to the process structure (see Roach [1993]), most, if not all, vectors defined in the spaces are physically realizable.

4. THE VULNERABILITY SPACES AS METRIC SPACES

One of the more desirable features of using a vector space for VL analysis is that of the distance between two vectors, especially if one is an empirically determined value and the other is analytically determined. In this case, of course, the distance between the two vectors may be an answer to the question of how well one has modeled the process. Although the full discussion of distances (or norms) in the spaces will be given shortly, it is important to realize that there are many norms definable on a given vector space. No mention has been made of any specific order in which the elements are to appear in the vectors, nor has anything been said about the relative importance of one component versus another. These concepts will play a role in determining an appropriate norm for a given VL space, as the following example demonstrates.

Suppose a certain experiment is performed in which a single damage mechanism (fragment) perforates an armor plate, ricochets off the edge of component No. 1, and lodges finally in component No. 2. Suppose further that the ricochet leaves component No. 1 undamaged. An analytical model of the experiment is run, with resulting output of plate perforation, ricocheting off component No. 3 (slightly damaging it), and finally lodging in component No. 2. How close was the model to the experiment? Suppose the model has the capability of using Monte Carlo techniques and is run a second time, with the result that the armor is perforated, and the fragment this time misses components No. 1 and No. 3, lodging in component No. 2 directly. Was this result "closer" to the experiment than the first model run, or not? Suppose component No. 2 happens to be sensitive ammunition, and the fragment impact in the experiment resulted in a catastrophic loss of the entire target. Are all three results equivalent? What if it took longer for the fragment to ricochet off components 1 or 3 than it did for the fragment to enter component No. 2 directly? That is, the catastrophic event for the second model run occurred at a different time T2 than either the experiment or the first model run. Does this mean it cannot be compared to vectors from a different T2? It should be quite clear that norms will play an important role in VL analysis and that the usual "distance function" in Cartesian space is not a useful one in the current context.

Nevertheless, it is quite clear from the discussion in the previous section that the usual root-sum-square Cartesian norm provides one example of a metric for each of the VL spaces, thereby demonstrating that they are indeed metrizable vector spaces. In particular, let X be any vector in any VL space,

$$X = (x1,x2,x3,...,xn,t),$$

and define the norm of X, ||X||, by

$$||X|| = SQT\{(x1)^{**}2 + (x2)^{**}2 + ... + (xn)^{**}2 + t^{**}2\}.$$

This norm gives each n-tuple in the spaces a length. Each n-tuple has a direction uniquely defined by its direction cosines, DCi,

$$DCi = Xi/||X||, i=1,2,...,n.$$

Thus, each n-tuple in each VL space is indeed a vector. Finally, since Z=X-Y is in the VL space if X and Y are, then one defines the distance between X and Y as the norm of Z. This function clearly defines a metric on the VL space.

It is worth reiterating that it is not claimed that the usual Cartesian metric presented here will be useful in the solution of VL analysis problems. The goal here is simply to demonstrate that the VL spaces are metrizable vector spaces; this has been done. It must also be noted that no attempt has been made to reconcile the physical units of this metric. Summing the squares of position, velocity, acceleration, etc. values is unlikely to represent some physically significant quantity.

5. THE CONTINUITY OF THE MAPPINGS BETWEEN SPACES

Let us next consider the mappings from a space at one level to a space at another level. Fundamentally, the points in the spaces are determined by system design and construction, and by weapon delivery parameters. The mappings are characterized by empirical or theoretical relationships such as penetration algorithms, fracture mechanics, etc., in the case of the O12 mapping, or engineering analysis, for example, for the O23 mapping.

There is variability observed in penetration data, in the fracture mechanics of spall formation, and in other parameters associated with threat/target interaction. Whether this variability is a function of a lack of understanding of the physical mechanisms by which damage occurs, the inability to measure accurately the appropriate parameters, or something fundamental a la Heisenberg, is moot. What is important is to realize that this variability is a characteristic of the mapping function, not its domain or range space; that is, two applications of a mapping function to the same point in its domain may result in two different image points in its range. The same comments may be made about observed variability in engineering performance. Engines with "identical" leaks of coolant may take different amounts of time to seize, for example. Again, this variability is a characteristic of the mapping, and not of the spaces. As has been stated elsewhere, there is also some variability introduced by the time smearing involved in the damage assessment process.

Repeated applications of O12 from the same point in VL1 can provide an indication of the likelihood that a certain damage state vector in VL2 will occur from a given set of threat/target initial conditions in VL1. Similarly, repeated applications of O23 can be used to generate likelihood estimates for achieving particular capability states. These likelihoods, from which probabilities may be inferred, are associated with each point of a range space at level n by the mapping O from level n-1 to level n. If the mapping is changed due to addition or deletion of "knowledge," then the associated likelihoods, or frequencies of occurrence, will also change; the points in the domain and range spaces are unaffected.

With the introduction of metrics in each of the spaces, the concept of continuity of the mappings is straightforward. The mapping O, from space VA to space VB, is continuous if, given $e>0$, there is a $d>0$ such that

$$\|O(x) - O(y)\| < e \quad \text{whenever } \|x - y\| < d,$$

for every pair of points (vectors) x and y in VA. The value of the concept of continuity in the context of VL analysis is, of course, the ability to formalize the notions that "initial conditions which are 'close' produce damage states which are 'close'," and "damage states which are 'close' produce capability states which are 'close'." In addition, it may be possible to use the wealth of knowledge concerning approximation of continuous functions to measure the degree to which an approximation to O12 or O23 reflects reality.

6. APPLICATIONS TO VULNERABILITY ANALYSIS PROBLEMS

In this section, we consider several classes of problems for which the VL process structure, and specifically the associated mathematics, provides new insights and solution techniques. The examples here are intended to serve as thought pieces, and are not fully developed analytical techniques. Throughout these examples, reference is made to comparing vulnerabilities or lethalities without specifying at which level or levels it is most appropriate to make that comparison. For the most part, the author believes it is important to compare vulnerabilities and lethalities at level 3. There are many reasons for this belief, some philosophical, some mathematical. A full exposition of the rationale for making VL comparisons at level 3 is the subject of a future report by the author.

Example 1. Comparison of Model Output With a Live Fire Shot

This is an example of a classic problem: a model produces one output, while an actual shot produces a different output. The pertinent questions are, "What specifically is it that caused the model output to be different from the actual shot?" and "How 'close' are the two results?" Given the fact that the two results are vectors in a closed vector space on which a suitable metric has been defined, the second question is easily answered by computing the distance between the two points. This raises yet another question, namely, "How close is 'close enough'?" At least a part of the answer lies in the causes for "incorrect" model output. The VL process structure provides a clear audit trail for investigating such problems.

Specifically, suppose one wishes to compare the outputs at level 2. One begins by ensuring that both the empirical and the analytical O12 mapping had the same domain point. That is, the initial conditions for both "experiments" must have been identical. If they were not, one need only rerun the analytical experiment with the appropriate initial conditions and compare again with the empirical result. The next step is to see if the range points, or damage vectors, are a part of the same space VL2. That is, both damage vectors must be expressed at the same level and with the same granularity. This is actually a nontrivial point because of the subtleties involved in the damage assessment process. A short digression is in order.

Frequently, the target damage assessment process results in a mix of information, some at level 2 and some at level 3. The classic example is boresight shift in a tank target. Boresight shift is a measure of the difference between the gun pointing angle and where the sight indicates the gun is pointing. Such shifts can occur because of thermal bending, ballistic shock, or physical deformation due to ballistic impact. Now, boresight shift is measured pre- and post-shot and recorded as a part of the damage assessment. But boresight shift is a capability, not a "damaged component." Thus, while broken sights, ruptured fuel cells, and the like are clearly level 2 entries in the post-shot record, boresight shift is a level 3 entry. Moreover, there may be no visible level 2 damage contributing to that boresight shift. In other words, a "perfect" analytical model may show as output (due, say, to ballistic shock) a slightly bent sight mount; that slight bend may be neither visible nor measurable in the field. Clearly, care must be taken to ensure that any differences observed between empirical and analytical results are not artifices of the manner in which the results are expressed.

Once the initial conditions (domain points) are identical and the damage vectors are expressed at the same level and with the same granularity, any differences in range point (damage vector) are due to one of two possible characteristics of the O12 mapping: the natural variability of the physics of threat/target interaction or inaccuracies or deficiencies in the analytical description of that physics. While it may be difficult, in practice, to distinguish between these two possibilities, the first is a problem in statistics, and the second is a problem in physics. Adequacy of the algorithms for describing the damage due to penetration, spall, shock, fire, or toxic fumes must be examined, with due consideration given to the aforementioned variabilities. Riccochet, jet bifurcation, and other such phenomena must be adequately treated. The important point here is that, at this stage, it is clearly the level of understanding of the physical phenomena and their variability which is at the heart of empirical/analytical differences. That is, the problem is one of science, not misinterpretation or improper input/output comparisons.

Note that precisely the same type of process applies when comparing outputs at level 3, where one is concerned with the domain and range of the O23 mapping and with the engineering aspects of target function.

Example 2. Selection of Appropriate Shot Lines to Determine System Vulnerabilities

There are two types of vulnerability problems which fall under this example: What is the vulnerability of system A to munition B? or, What is the vulnerability of subsystem C of system A to munition B? There are three ways to attempt to answer these questions: analytically, experimentally, or a combination of the two. The classical response to a proposed experimental solution is that one simply has insufficient threats, targets, or money to do all the shots necessary to determine the requisite vulnerabilities. This response, while doubtless true, is based on the assumption that large numbers of shots would be required, without actually having a sense of the order of magnitude of "large." Similarly, even given total confidence in a "perfect" analytical model, the prospect of running all possible shot lines (literally, an infinite number!) through a system is a daunting computer task. Moreover, were it possible to make this infinite number of computations, one needs to decide what sense to make of the infinity of individual results.

To view this problem in the context of the VL process structure, recall the mathematical notion of a basis for a vector space (see, for example, Greenberg [1978]):

> The set S of linearly independent vectors, S={X1,X2,X3,...,Xm}, forms a basis for the space VLn if, and only if, every vector Y in VLn can be written as a linear combination of the vectors in the set S. That is, if Y is in VLn, then there exist constants a1,a2,a3,...,am, such that Y=a1*X1+a2*X2+...+am*Xm.

The set S is said to span the space VLn. Similar terminology pertains to subspaces. Now, if one is able to find a set (and there are, in general, many such sets) of basis vectors for VLn, then one need only generate analytical or empirical data along those basis vectors in order to determine all vectors in the space.

While it may not be simple to distinguish physically realizable vectors from nonphysically realizable vectors generated this way, it is still possible to make generalizations about the class (space) of vectors as a whole. Moreover, while generating m shot lines analytically or empirically may still be costly at best or impossible at worst (since m may be countably infinite), there is at least an indication of how many and which shot lines are necessary to "solve" the problem.

If the problem has to do with the vulnerability of a subsystem, such as hydraulics, then it is interesting to consider whether the "hydraulics vectors" form a closed subspace of VLn, at level 2 or level 3. More specifically, if VLn has vectors of the form

$$X = (A,B,C,...,H1,H2,H3,J,K,...),$$

where the H1, H2, and H3 are either hydraulics-related components or capabilities, then the set of vectors of the form

$$H = (0,0,0,...,H1,H2,H3,0,0,...)$$

for all values of H1, H2, and H3 in the original VLn do indeed form a subspace, closed under addition, subtraction, and scalar multiplication. Thus, to look at the vulnerability of the hydraulics subsystem, one need acquire or generate data only for a set of basis vectors (in this simple example, only three are needed) for the hydraulics subspace. The real value of this concept is demonstrated in Examples 3 through 5 below.

Example 3. Evaluation of Vulnerability Reduction Techniques

One of the most difficult tasks facing a vulnerability analyst is to determine the relative efficacy of one vehicle configuration over another in terms of reducing vulnerability. The difficulty is caused by trying to compare damage or capability along "the same" shot line in two different vehicle configurations, since the shot line passes through different components in each version of the vehicle. Thus, for example, one vehicle version, say the XM9, may have a supposedly less vulnerable hydraulic system than does the XM8. The XM9's hydraulic system may have entirely different components, located in an entirely different place, and with an entirely different functional connectivity than the hydraulic system in the XM8. Shot lines through the hydraulics of the XM8 may pass nowhere near the hydraulics of the XM9, so that "shooting the same shot lines" at both vehicles provides no basis for determining the efficacy of the "less vulnerable" XM9 hydraulics.

Using the VL process structure, and in particular the hydraulics subspace of Example 2, the basis vectors for each hydraulics subspace can be generated, and the respective vulnerabilities can be determined. At this point, a suitable method for comparing the two "vulnerabilities" must be found. One such method is described in the next example. The important point here is that selecting the "shots" necessary to determine the complete solution to the problem can be done in a precise analytical fashion.

Example 4. Comparison of the Vulnerabilities of Two Combat Systems to a Given Munition, or the Lethalities of Two Munitions Against a Given Combat System

The first part of this example, comparing the effects of a munition on two different systems, is really identical to Example 3, but, in this case, one might have all subsystems of each vehicle being entirely different. To the extent to which the elements of the vectors in the space at the level chosen for comparison can be made identical for each vehicle, the vulnerabilities can be compared. For example, suppose the problem is to compare the vulnerabilities of two tanks A and B to a single threat munition, and this comparison is to be made at level 3. Since A and B are both tanks, they will certainly have a number of capabilities in common. If the analyst chooses the finest level of granularity for which both

A and B have identical elements in the vectors in their respective spaces VL3, then comparisons can be made just as in Examples 2 and 3.

Suppose tank A has a turbine engine, while tank B has a piston engine. Clearly, one cannot use a level of granularity which contains piston ring capability or turbine blade capability. One could, however, use a level of granularity recognizing motive force. Note that in this manner of selecting the level of granularity, it is the accuracy of the (single) solution space which drives the analysis, and it is unnecessary to make an "apples-to-oranges" comparison between two different levels of granularity. One notes also that in the case of tanks A and B, it is a rather straightforward analytical process to make the comparison at level 3. At level 2, given the two different engines, no such comparison can be made.

In the second type of problem, since there is but one target system, granularity of the spaces at any level may play a different role. In this case, while one still needs the granularity of the comparison spaces (one at the same level for each munition) to be the same, the level of granularity here depends on the nature of each munition's damage mechanism. For example, a comparison of two blast munitions will probably require less detail about interior components (at level 2) than will, say, a comparison of two kinetic energy penetrators at that same level. Note, however, that comparisons made at level 3 will likely always use the same granularity of target capabilities. This fact would make comparison of a blast munition with a kinetic energy penetrator straightforward at level 3, while such comparison would be extremely difficult at level 2.

The point of this example is that the best level at which to make comparisons of vulnerability or lethality is level 3, the capability state.

Example 5. Evaluation of Surrogate Threat and/or Target Suitability

As a final example, consider the problem of needing vulnerability information on a target and/or munition for which no data exists. A common approach in the situation is to assume that the target and/or the threat munition behave very much like some other target or munition about which vulnerability data exists. The question is, how close is (are) the surrogate(s) to the desired threat/target combination? One approach to this problem is to develop spaces at level 2 or level 3 which have a granularity consistent with the degree to which certain properties of the surrogated target or munition are known. For example, if the surrogated target is a tank, it must move, detect and acquire targets, shoot, and communicate, at a minimum. The extent to which one can hypothesize similarities in the processes by which the surrogate performs these functions is one measure of the level of confidence one might have in using the surrogate in a vulnerability analysis. Note that here too, as in an earlier example, the granularity of the points in the spaces dictates the "accuracy" of the analysis.

Having developed the spaces at the appropriate level and with the appropriate granularity, evaluation of the applicability of the surrogate target or munition is a matter of determining the distance between the vector from the surrogate and the actual target or munition. The most difficult part about such an evaluation is determining how close is close enough.

7. CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that one can define metrizable vector spaces at each level in the VL process structure. Several examples have been given illustrating the utility of the mathematical structure as applied to classical problems in vulnerability analysis. These examples are intended as thought pieces; actual application of the concepts is far from trivial. Nevertheless, the potential for mathematical rigor is intriguing. Although little has been said in this report about the continuity of the O12 and O23 mappings, there is hope that one might be able to use the power of the theory of approximation of continuous functions to assess the "goodness" (that is, accuracy, sufficiency, etc.) of algorithms used in vulnerability analysis. It is also the author's feeling that there are other, more powerful (in the sense of VL analysis) metrics which could be defined on the spaces, providing insights into the solutions of other significant problems. Clearly, much remains to be done. It is hoped that this report will generate thought, discussion, clarification, and expansion of these ideas.

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