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Engineered Resilient Systems: A DoD Perspective

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Abstract

Department of Defense (DoD) systems are required to be trusted and effective in a wide range of operational contexts with the ability to respond to new or changing conditions through modified tactics, appropriate reconfiguration, or replacement. As importantly, these systems are required to exhibit predictable and graceful degradation outside their designed performance envelope. For these systems to be included in the force structure, they need to be manufacturable, readily deployable, sustainable, easily modifiable, and cost-effective. Collectively, these requirements inform the definition of resilient DoD systems. This paper explores the properties and tradeoffs for engineered resilient systems in the military context. It reviews various perspectives on resilience, overlays DoD requirements on these perspectives, and presents DoD challenges in realizing and rapidly fielding resilient systems. This paper also presents promising research themes that need to be pursued by the research community to help the DoD realize the vision of affordable, adaptable, and effective systems. This paper concludes with a discussion of specific DoD systems that can potentially benefit from resilience and stresses the need for sustaining a community of interest in this important area.

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1. Background

The mission of the United States Department of Defense (DoD) is to equip and deploy the military forces needed to deter war and assure national security. To this end, the DoD needs to maintain force readiness, and be able to rapidly field required personnel and equipment to accomplish mission objectives. The systems that are deployed today and will be in the foreseeable future lie along a continuum from simple to complex. Examples of complex systems are cyber infrastructure systems, logistical data and information systems, and large-scale materiel solutions such as fixed-wing aircraft and naval vessels. In this paper, we focus on the third category (materiel), noting that both the nomenclature and reasoning apply to other systems as well. This assertion is based on the fact that all systems are expected to be trusted and effective in a wide range of operational contexts with the ability to respond to new requirements through new tactics, appropriate reconfiguration, and timely replacement.

Due to the nature of the threats to the Nation and its armed forces, the DoD will continue to deploy its materiel throughout the world for the foreseeable future. This makes the DoD unlike any commercial enterprise in that its mission remains relatively unchanged for decades and generations in the face of unexpected, unanticipated, and emergent situations. This recognition provided the impetus for this paper.

Previously, Neches et al.¹ described resilient systems as follows:

“A resilient system is trusted and effective out of the box in a wide range of contexts, easily adapted to many others through reconfiguration or replacement, with graceful and detectable degradation of function.”

This definition accounts for the fact that military missions can range from non-kinetic operations (e.g., Humanitarian Assistance and Disaster Relief) to kinetic operations and conflict with, for example, near-peer states. Today’s rapid changes in missions and mission requirements, as well as the emergence of new asymmetric threats in the operational environment, create uncertainties and surprises that have to be dealt with on-the-fly. Furthermore, ready global access to commercial technology pose risks and diminish trust in DoD systems and system-of-systems.^{2,3}

Not surprisingly, in recent years there has been a dramatic increase in interest within the DoD to engineer systems that exhibit resilience in the face of the unexpected and the unknown. This surge in interest is also fueled by the recognition that as systems continue to increase in scale and complexity, traditional fault protection approaches will no longer suffice from both cost and coverage perspectives.⁴

This paper is organized as follows. Section 2 reviews the characteristics of resilience from a broad perspective. Section 3 presents a DoD perspective on the concept of resilience and engineered resilient systems. Section 4 discusses engineered resilient systems challenges and potential mechanisms for introducing resilience in systems. Section 5 offers concluding comments including a discussion of the future of engineered resilient systems in the DoD.

2. Perspectives on Resilience

Although resilience is rapidly becoming a common theme in a variety of fields, defining and measuring it largely depends on the problem domain. In October 2013, a workshop co-sponsored by the Military Operations Research Society (MORS) and Argonne National Laboratory examined several analytical issues associated with enhancing societal and regional resiliency¹³. The participants in this workshop defined resilience as “the ability of an entity — e.g., asset, organization, community, region — to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance from either natural or man-made events.” This definition is more encompassing than most in that it subsumes several resilience characteristics included in narrower definitions of resilience. Specifically, the workshop definition covers the following key properties:

- Ability to Repel/Resist/Absorb Disruptions (natural or manmade)
 - Ability of a system to return to its original state or move to a new, more desirable state after being disturbed⁵
 - Resilience in Ecological Systems is the measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables⁶
 - Ability of a system to achieve envisioned (science) objectives even if the system (spacecraft) performance, health, and/or environment are not as expected⁷
 - “Ability of a system to circumvent, survive, and recover from failures to ultimately achieve mission objectives. A resilient system is able to reason about own/environmental states in the presence of environmental uncertainty”.⁸
- Ability to Recover from Disruptions (disasters or catastrophic events)
 - Ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations, even after a major mishap or in the presence of continuous stress.⁹
 - Resilience in Social Ecological Systems is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.¹⁰
 - Focus of Interest: The Resilience Framework in Engineering – The management of decision making in the trade-off space with respect to “disruptions, system attributes, methods, and metrics”.⁴
- Ability to Adapt to New or Changed Conditions (man-made threats or natural disasters)
 - “Cultural resilience refers to a culture's capacity to maintain and develop cultural identity and critical cultural knowledge and practices. Despite challenges and difficulties, a resilient culture is capable of maintaining and developing itself.”¹¹

While many of these definitions are focused on organic and ecological systems, these characteristics also apply to military systems. In fact, the DoD has emphasized the need to improve the resiliency of both its uniformed and civilian personnel. Consequently, the foregoing perspectives on resilience offer a sound basis to begin a meaningful discussion of resiliency for DoD systems.

3.The DoD Perspective on Resilience

The DoD perspective on resilience subsumes several earlier definitions. However, the DoD is now required to engineer systems that exhibit specific resilience properties: ability to Repel/Resist/Absorb; ability to Recover; and ability to Adapt. While these characteristics are necessary for national defense, they are not sufficient. In addition to these characteristics, DoD systems are expected to perform effectively in a wide range of operations across multiple potential alternative futures despite experiencing disruptions. This ability or property is termed Broad Utility.¹²

In light of the foregoing, the four key properties of a resilient DoD system are: Repel/Resist/Absorb; Recover; Adapt; and Broad Utility (Figure 1). In this figure, the circles represent greater ability at the edges than in the center for each resilience property; the intersection of two or more circles can be viewed as providing a reasonably effective resilience solution. The intersection (i.e., nexus) of all four properties defines the space of resilient solutions with each solution in the space being proximal to an optimal solution for a particular property.

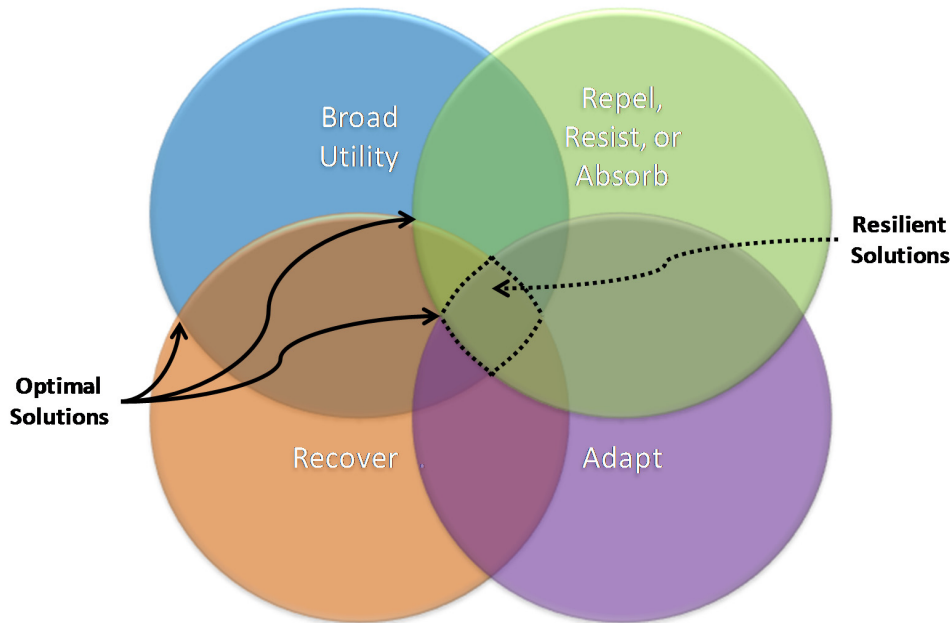


Figure 1. Properties of Resilient DoD Systems and System-of-Systems

Even under the best of circumstances, engineering a system for resilience is a daunting task because of the range of issues that need to be addressed. For example, design envelopes need to be understood in advance, and when a system fails, it must do so in a predictable, detectable, and graceful manner to enhance overall system survivability (i.e., survivability of both users and the other subsystems in the system). Within the DoD, systems or components that are not resilient are often labeled “disposable” or “consumable.” Several DoD systems exhibit two or more of the properties shown in Figure 1, making them suitable for use in multiple operational environments. However, as hardware and software technology allow for more advanced (i.e., sophisticated) defense systems, it is almost inevitable that the resulting system will be complex. As complexity increases, so does the cost of these systems. Despite limited resources, scientists and acquisition professionals are asked to develop capabilities that possess at least three if not all four of these properties- - a tall order.

Some legacy military systems have turned out, after the fact, to meet the DoD definition of resiliency. These include, but are not limited to, the Lockheed C-130 Hercules air frame, Boeing B-52 Stratofortress, M113 armoured personnel carrier, Bradley Fighting Vehicle (BFV), High Mobility Multipurpose Wheeled Vehicle (HMMWV), and, of course, Service Members. While none of these systems are resilient in the sense of Figure 1, their range of capabilities, coupled with the number of their variants/derivatives and their longevity, lend credence to the claim that they exhibit a fair degree of resilience. Furthermore, each of these systems satisfies initial operational requirements, has been in the US inventory for over three decades, has more than five basic variants, and has the capability to execute multiple missions.

It should be noted that the HMMWV has been criticized in recent years for its inability to repel enemy munitions. However, for its basic purpose as a four-wheel drive, cargo carrier, it has been quite versatile at performing its basic mission in nearly every operational environment and weather condition encountered by US forces since 1984. It has at least 17 variants in service within the U.S. Military, and within seventy other countries. Its variants serve numerous roles including cargo/troop carrier, automatic weapons platform, ambulance, missile carrier, howitzer/mortar prime mover, anti-aircraft platform, and communications shelter.

Today, the DoD must use such systems as the de facto standard for resiliency and a point of departure for enhancing the resilience of future systems in accord with the resilience properties shown in Figure 1. So, how can the

engineering of resilient systems in accord with Figure 1 be accomplished? This is the challenge that the DoD faces today. Fortunately, the materiel systems noted above could serve as a baseline from which the DoD can begin to anticipate and plan for resiliency for systems in the acquisition pipeline. However, before enumerating the engineering challenges and technologies needed to transform the current acquisition process, it is worth elaborating on the particulars of the four key resilience properties for military systems. For example, terms such as “lifetime,” “environment,” “disturbance,” “stress,” and “mission,” take on more specific meanings for DoD systems.

Table 1. Rationale for Resilience in DoD Systems

<ul style="list-style-type: none"> • Lifetime Operation • Actual Usage extends decades past original plan/design • Regular planned and unplanned overhauls • Periodic redesigns for service life extensions • Changing operational and regulatory environment • Designed for use in particular terrain and weather (e.g., desert) and used in another (wet) • Ability to perform in extreme climates • Accommodate new building construction techniques and materiel • Light Tactical Vehicle adapted for use with heavy armor • Shallow draft vessel used in deep ocean
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Of course, it is well understood that DoD systems are expected to perform a variety of operations such as combat operations and expeditionary operations. However, the DoD has learned from experience that the types of operations that a system can potentially be employed in are, at best, only partially predictable. Table 1 offers criteria and rationale for system resilience in DoD.

The types of operations that a system may be employed in are rarely predictable especially with respect to the level of their employment. As the U.S. draws down operations in the Middle East and reduces its military force structure, it will likely need to project that force from a limited number of consolidated bases. This requires a resilient expeditionary force that can rapidly deploy, and employ and sustain its capabilities in hostile territories and/or unstable regimes. Some of the key issues that affect the design and development of a DoD system operating in a combat or expeditionary operation include but are not limited to:

- Unknown and Uncertain Environments
- Mobile and Limited Support Structure
- Extreme Conditions
- Agile and Adaptive Adversary
- Changing Natural/Manmade Environments

Many of these systems are constrained by the current DoD Logistics System when it comes to the frequency and method of resupply. For example, availability of mobile refuelling platforms or limited varieties of fuels to maximise the ability to support new or unstable fuel forms or sustain refuelling operations in an austere environment. Since DoD systems remain in use for decades, they must be designed and built in a manner that allows them to be economically refurbished after extended use or after use in harsh environments. For example, wheeled vehicles invariably undergo major overhauls after returning from deployments to replace worn seals and components to extend their life span within the fleet. To achieve longevity, a platform must be modifiable and upgradeable during its time within a fleet to exploit advances in technology, correct deficiencies in the system, and replace components no longer in the inventory. This provides a fleet or systems generating a portfolio of capabilities or platforms that reduce risk by providing an array of systems viable for mission requirements and resilient to diverse conditions⁸

Resilience can also be achieved by exploiting the loose coupling between micro systems whose interactions give rise a complex macro capability that satisfies mission objectives. For example, multiple self-configuring, and

cooperating sensors can effectively provide a resilient web of data collectors by “swarming.” The resulting macro system would be capable of adjusting to the changing environment and atmospheric conditions based on the micro systems observing and communicating to a higher command and control entity. Such systems have been developed and tested for tracking the movement of supplies through commercial and combat logistics systems.

Defining a system in this fashion also helps in predicting its performance and projecting when it is likely to need maintenance or replacement to continue to deliver required capabilities. The degradation function for a system provides insights in to when a system is no longer able to operate in resilient fashion within the space defined by the intersection of its resilience properties (Figure 1).

4. DoD’s Resilience Engineering Challenges

In light of the foregoing, we address the need for engineered resilient systems in DoD. To begin with, DoD systems have to cope with a wide range of missions with high degrees of uncertainty and risks. These missions range from non-kinetic operations such as Humanitarian Assistance and Disaster Relief (HA/DR) to conflicts with near-peer states. Rapid changes in missions, threats and operating environments create uncertainties in military requirements. Compounding the problems is the fact that commercial technology is now globally available to both friends and foes. Dependence on global technology poses trustworthiness risks for the DoD.

Resilience in a DoD system is the ability of a family of products to serve effectively in a variety of missions with multiple alternative futures through rapid reconfiguration or timely replacement despite uncertainties about individual component performance¹. Thus, as characterized by the Engineered Resilient Systems (ERS) program¹⁵, a resilient system in DoD: is trusted and effective in a wide range of mission contexts; is easily adapted to many others through reconfiguration and/or replacement, and; has predictable, graceful degradation of function^{14,16}.

A key ERS research challenge in the DoD is to develop and field “affordably adaptable & effective systems” by examining “mission volatility and uncertain futures”.^{1,12} The means by which such a capability can be realized is through a combination of techniques shown in Table 2.

Table 2. ERS Strategies for DoD Systems

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| <ul style="list-style-type: none"> • Calculating Leading Indicators <ul style="list-style-type: none"> – to assess consequences of technical/programmatic decisions and controlling risks • Performing the right trade-offs in a timely fashion <ul style="list-style-type: none"> – to maintain safety margins and controlling/avoiding drift • Developing an accurate model of drift <ul style="list-style-type: none"> – to understand risk factors for effective risk management • Developing applicable and realizable resilience heuristics <ul style="list-style-type: none"> – to inform and guide resilient system design • Developing appropriate resilience metrics <ul style="list-style-type: none"> – to evaluate candidate resilience strategies |
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Additionally, the analysis of such systems needs to be adaptable to the process within which the system operates, and the products that are being developed. This means that there is a need for an adaptive tradespace analysis based on the purpose of the capability and the missions in which it is expected to be used. Mission context, how a system helps to meet the desired end state of an operation or a series of operations and still be available for future operations, must be accounted for when designing a resilient platform that is expected to provide the capability. Disposable systems are viable for certain operations; however, the affordability of disposable systems, or limited supplies of complex systems is not always possible. One must assess the affordability of any system, disposable or resilient, to conduct a meaningful comparison of solutions. This approach is especially prudent in resource-constrained environments.

Finally, cost analysis needs to be coupled to mission context and grounded in physical reality and physics. The complexities of the environments, cost, and the massive effects of modern defensive systems limit the ability to conduct an adequate number of real world experiments. Often this limits data collection to that required to validate models and forecast likely performance. The use of modeling and simulations to fill the massive tradespace of possible uses and complex interactions of systems is essential in assessing the potential value of a system. Today, both industry and governments use high performance computing assets with validated models and simulations to replicate physics-based interactions and forecast system functionality to predict likely impacts on mission execution in a variety of mission contexts. The data generated by these models and simulations can be assessed and the resulting information can be used to inform trades-based discussions within the DoD. These trades are used to determine the risks in a system's ability to provide required capabilities as well as to determine whether or not a system can retain and exhibit sufficient resilience to warrant system acquisition and employment.

5. Conclusions and Recommendations

The general definition of resiliency and the particulars that constitute a resilient system depend somewhat on the discipline and the framework employed for discussion. For the DoD, a slight variant of the definition given in the introduction still applies:

A resilient system is trusted and effective out of the box, can be used in a wide range of contexts, is easily adapted to many others through reconfiguration and/or replacement, and has a graceful and detectable degradation of function.

In practical terms, resilient DoD systems need to be able to leverage new technologies and techniques as they appear, meet changing requirements, conform to new environments, and successfully meet the challenges of an adaptive foe. But, these systems also need to be manufacturable, deployable, sustainable, modifiable, and cost effective to be viable for inclusion in the force structure. Thus, the DoD must design its weapons systems to be resilient at the outset. To achieve this objective, strategic DoD programs such as ERS¹⁵ will continue to invest in key technology enablers such as tradespace analysis, affordability analysis, modeling and simulation, and other approaches to develop affordable, resilient systems and systems-of-systems. These approaches are key enablers for the DoD to accomplish one of its primary missions, the safeguarding of national security for this generation and beyond.

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