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REGULAR PAPER

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Toward a methodology for the system integration of adaptive resilience in armor

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Abstract

This article introduces a novel augmentation to systems engineering methodology based on the integration of adaptive capacity, which produces enhanced resilience in technological systems that operate in complex operating environments. The implementation of this methodology enhances system resistance to top-level function failure or accelerates the system's functional recovery in the event of a top-level function failure due to functional requirement shift, evolutions, or perturbations. The research expands system engineering, design, and integration methodologies, which currently do not explicitly address system adaptation and resilience, through the definition and demonstration of a methodology to integrate adaptive resilience and demonstrates its implementation in a relevant armor system case study. The methodology accomplishes this objective by defining adaptive design considerations, identifying controllable adaptive performance factors, characterizing adaptive performance factors and configurations, mapping and integrating adaptive components, and verifying and validating the adaptive components and configurations that achieve system requirements and adaptive design considerations. The utility of this research is demonstrated through development of an adaptive resilient armor system called the mechanically adaptive armor linkage (MAAL), which was designed, developed, and validated using the methodology for the system integration of adaptive resilience (MSIAR). The conceptual validity of the methodology is proven through a physical comparative test and evaluation of the system described in the case study. The research and resulting methodology supplements and enhances traditional systems engineering processes by offering systems designers the opportunity to integrate adaptive capacity into systems, enhancing their resilient resistance, or recovery to top-level function failure in complex operating environments.

KEYWORDS
adaptive resiliency, adaptive physical components, mechanically adaptive armor linkage (MAAL)

1 | INTRODUCTION

Systems engineers design, develop, and field traditional systems to address a set problem or fixed set of requirements that the system's functionality solves or fulfills. These traditional systems tend to operate at one optimized design point for a given set of external operational conditions to achieve a given top-level function or task. This approach, while acceptable for most systems, presents a significant functional limitation for systems that must operate or function in complex environments. Complex environments can be defined as environments in which operational conditions are unpredictable, experience disruptive perturbation, and rapidly shift.

This article proposes a new system attribute called *adaptive resilience*, which enables a system to adapt its functional traits, structure, process, and/or identity in order to maintain or regain functional effectiveness in satisfying its top-level functional requirements. This attribute is particularly beneficial in complex operating environments. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range or capacity for adaptation early in the design and development process. This article demonstrates such an integration methodology, which achieves the desired attribute of adaptive resilience. This research is described in much greater detail in the dissertation of the primary author.[1]

All technological systems operating in complex environments are disadvantaged when they encounter operational circumstances that may cause them to fail to achieve and maintain their top-level function. Traditional static system designs often fail in complex operating environments due to their inability to readily adapt to changing functional requirements. Contemporary fixed system designs (design for

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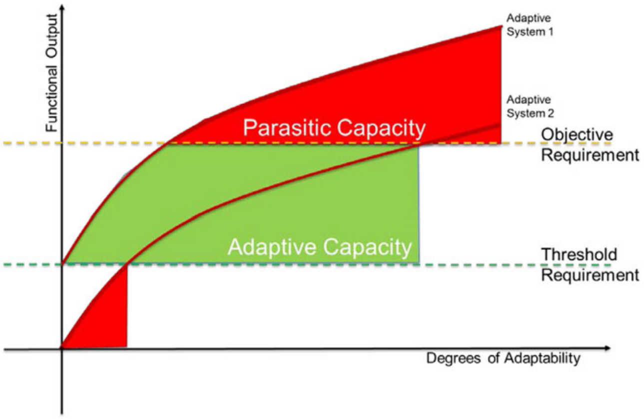


FIGURE 1 Adaptive capacity versus parasitic capacity

robustness) are better suited for operation in uncertain environments. However, they likely possess parasitic capacity created by their robust nature and are ultimately susceptible to failure complex environments because they also employ fixed functional states. Parasitic capacity is underutilized functional capability that detracts from adjacent functional capabilities within a system. Adaptive resilient system designs possess adaptive physical components that enable the system to resist or recover from functional failure in complex operating environments in an agile fashion, while simultaneously mitigating the effects of parasitic capacity (see Figure 1).

Within a system, adaptability is the key element that produces resilience. A system can only adapt to a purpose or a situation if it has the capacity to adapt or if some means of intelligence externally influences the system to adapt its use to new ends. Adaptive capacity is the critical system attribute that produces system resilience.[2] Adaptive capacity can be defined as the extent to which a system can adapt or absorb a functional disturbance without completely losing operational performance of a top-level function.[2] Parasitic capacity can exist in robustly designed systems as a catch all approach to functional requirement accommodation, or it can exist in adaptive resilient system when extensible functional states are desired.

Adaptive capacity can be further decomposed into modes of adaptability. Modes of adaptability are the ways and means to restructure or reconfigure a system's functional traits, structure, process, and/or identity. Two modes of adaptability—internal reconfiguration and external reconfiguration—serve to achieve the desired adaptation. Adaptations that occur through internal reconfiguration use means such as processes, mechanisms, and artifacts within the system to achieve desired functionality. Internal reconfiguration can occur through four means: operational variation, reallocation, degeneracy, and exaptation. External reconfiguration involves external means to achieve desired system functionality. Adaptive Mode 1 includes adaptive means present within the system at the time of the functional disturbance or incident. Adaptive Mode 2 involves external means (eg, mechanisms, processes, and artifacts) not present in the system when its functionality was lost, but when applied after the fact, allows the system to regain its functionality. External reconfiguration occurs through three means: progressive scaling; redundant scaling; and replacement, repair, or healing.

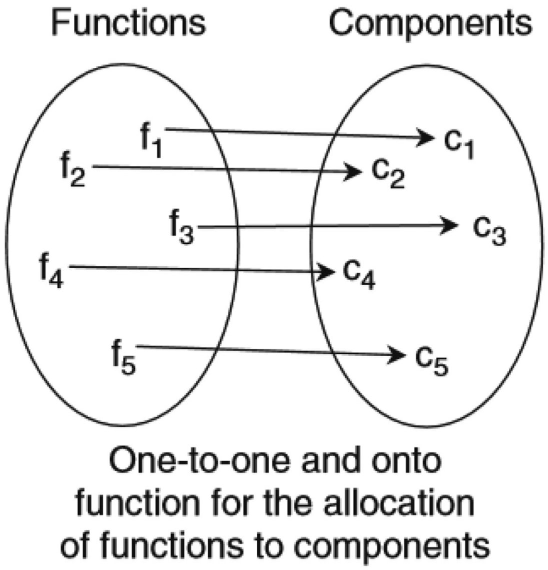


FIGURE 2 System functions and physical components mapped through an allocated architecture[4]

The purpose of adaptive resilience is to enable a system to adapt its functional traits, structure, process, and/or identity in operationally relevant timescales in order to maintain or remain functionally effective in satisfying its principle/top-level functional requirement in an unknowable and rapidly shifting environment. In order to achieve an adaptive resilient system, system designers and engineers must identify, account for, and incorporate the necessary range of performance-trait adaptability or adaptive capacity early in the design and development process. Therefore, an effective integration methodology is required to achieve system-level adaptive capacity during the system design and development process.

2 | TECHNICAL APPROACH AND METHODOLOGY

2.1 | Summary of design approaches

The methodology for the system integration of adaptive resilience (MSIAR) builds on prior design approaches and paradigms such as axiomatic,[3] allocated design,[4] set-based design,[5] as well as methods, which employ model-based systems engineering (MBSE) and tradespace analysis to mitigate the consequences of uncertainty in the system's functional design.[6,7] The problem with these contemporary design approaches is that they result in a fixed design. All of this information from tradespace analysis and delaying design decisions is helpful in making good system designs for static and uncertain environments. But the complex environment by nature makes the very most informed designs disadvantaged because the requirement will still change. A system must be able to rapidly change with the environment to be resilient to it. This is not to write off these approaches as unsuitable, just incomplete for complex operating environments. This is where adaptive resilience can take a system design to the next level.

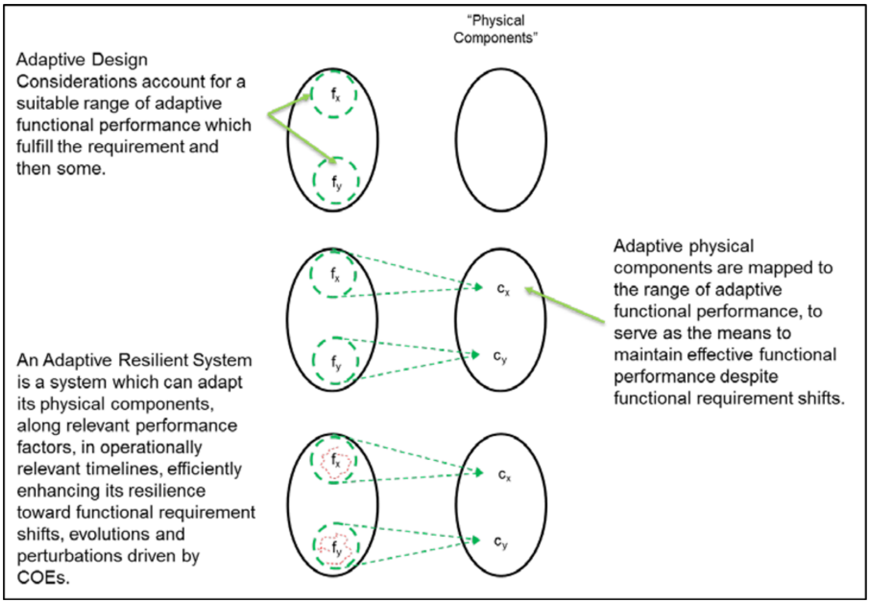


FIGURE 3 Allocated architecture with adaptive resilience

2.2 | The methodology for the system integration of adaptive resilience (MSIAR)

The MSIAR transcends these methods by placing emphasis on the adaptive resilient physical component design. By doing this the components are enabled to accommodate a broad range of functional requirements while simultaneously mitigating the effects of parasitic capacity. Instead of simply mapping the physical components to the functional requirement, as Buede shows in his approach seen in Figure 2, the MSIAR methodology is designed to account for potential functional requirement shifts, perturbations, and evolutions. The MSIAR seeks to reveal where system functions could potentially evolve over a range of requirements instead of just one and then maps adaptive components capable of accommodating the functional range. This is depicted in Figure 3.

The MSIAR, as seen in Figure 4, utilizes seven high-level steps that can be decomposed to any requisite level of fidelity for the integration effort of interest. The seven steps are as follows:

1. *Define adaptive design considerations*: The first and most critical step to integrating adaptive resilience is defining the desired adaptive design considerations and identifying the manner in which they are adaptive. The standard pickup truck is powerful and full of utility for situations in which power and torque are needed. However, this attribute is a detractor for alternate uses of the pickup truck such as simple transportation or commuting. Driving a pickup truck 50 miles every day is on average more costly from a fuel perspective than driving a compact car. Conversely, a compact, fuel-efficient car is much less costly for commuting and simple transportation from that same fuel perspective. However, the compact car is not suitable for pulling a large trailer or hauling cargo. A potentially better option would be to have a truck that provided the power when needed, but when the power was not needed, could be reconfigured in a manner that optimized fuel efficiency and normal use costs.
2. *Identify controllable/adaptive performance factors*: Systems engineers and designers understand what parameters can be manipulated and adapted to achieve the desired range of adaptive performance. Functional parameters or factors are independent attributes of a function that dictate the performance or output of that function. Controllable means that the factor can be manipulated easily and in an agile fashion, which is critical because if the factor cannot be controlled, then the user cannot predictably adapt it for desired performance.
3. *Characterize adaptive performance factor configurations*: Performance factor solution configurations are the factor states that meet or advance the system's performance toward the desired function performance specified in the requirements.
4. *Verify and validate adaptive performance factor configurations*: Verifying and validating the resultant factor configuration solutions is critical to being able to predict accurately or even approximately the outcome of a system adaptation. Verification ensures the adaptive performance factor configurations actually achieve the desired system performance. Validation ensures that verified adaptive performance factors conform to the adaptive design considerations and system functional requirements specified in step 1.
5. *Map validated configurations to adaptive system components/modules*: Mapping the configuration solutions to physical subsystems and components capable of producing the configuration states and functional outputs consists of identifying physical components that have the configurability to enable the overall system to operate at the identified configuration factor states. If subsystems or components do not exist with this capability, a design and engineering process must occur to create them or to integrate that capability into existing systems.
6. *Integrate adaptive components and configurations into system*: The level of integration for this step is much more in-depth, compared

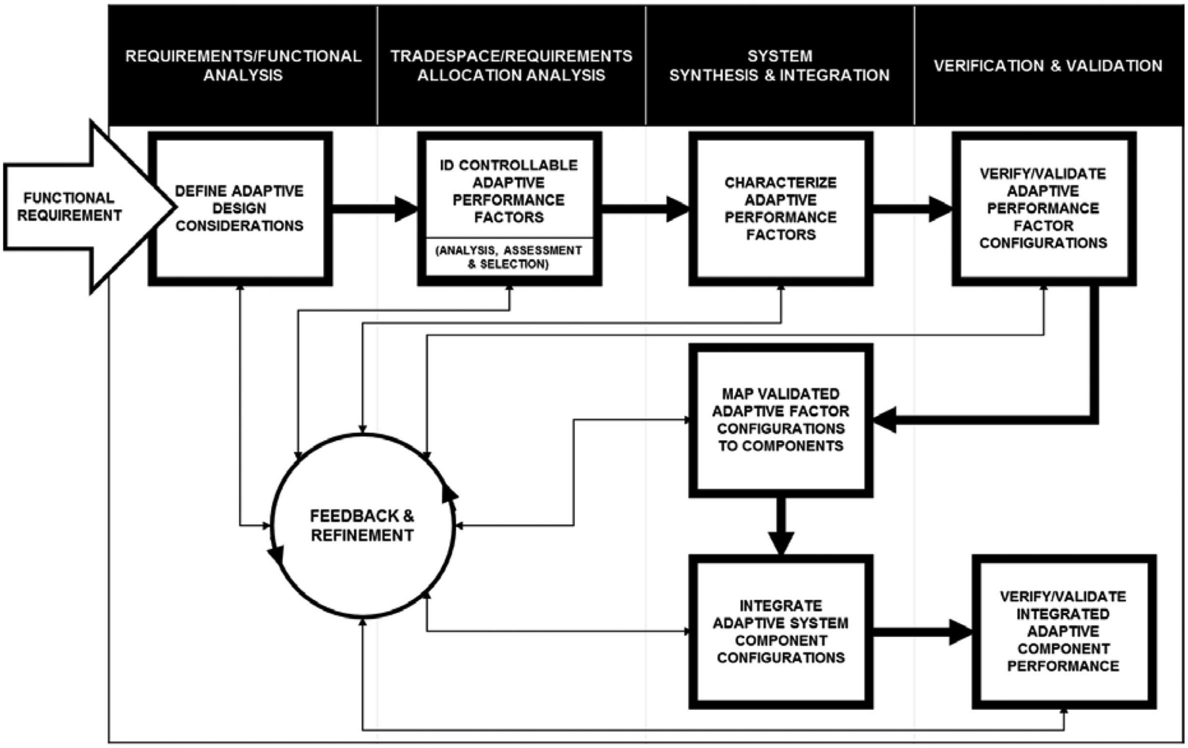


FIGURE 4 The methodology for the system integration of adaptive resilience

to the previous step, and requires analysis of overall system impacts on the vehicle. All traditional system engineering and integration principles apply in this step of the methodology.

7. *Verify and validate integrated component configurations and performance*: The integrated adaptive component performance must be verified and validated against the functional requirements of the overall system. The purpose of this step is to ensure that the physical system components are capable of physically performing at the functionally required ranges of output. Verification ensures the integrated components actually achieve the desired system performance, and helps characterize the performance in case there are system-level synergistic or nihilist effects from the combinations of adaptive performance factors. Validation ensures that verified integration of components conform to the adaptive design considerations and system functional requirements specified in step 1.

3 | APPLICATION AND METHODOLOGY DEMONSTRATION

3.1 | Overview of mechanically adaptive armor linkage (MAAL) technology

In this study, the seven-step methodology was applied to the design of a novel armor system as a case study to demonstrate its efficacy in integrating the adaptive capacity that produces system adaptive resilience. The case study used the draft capability definition document for the U.S. Army Ground Combat Vehicle (GCV) as the basis for the protection, mobility, and transportability requirements. These requirements were used as the inputs to the methodology, which generated adaptive design consideration. These MSIAR-generated design considerations specified a range of protection, considerations for the competing mobility, protection interests, and limitations on the vehicle width for transportability purposes. These considerations are listed in Table 1. These considerations were then used to identify controllable performance factors that relate to and influence the realization of the design considerations. The adaptive factor configurations for the novel armor system of interest were *armor mass, dimensionality, and dynamic state*.

The case-study application of the methodology resulted in the creation of an adaptive resilient armor demonstrator, which employs a novel armor technology (that includes a patent for the primary author) called mechanically adaptive armor linkage (MAAL). The MAAL armor system provides enhanced passive armor ballistic protection through passive dynamic deflection and ability to accumulate mass at the point of threat impact on the armor strike-face. The MAAL armor system causes a yaw effect on ballistic threats because of reactive tension in the MAAL armor strands acting on the threat and after impact with the threat. Because of the dynamic capacity in the fundamental link structure, the MAAL armor can also be implemented through numerous embodiments. Because of these features, the MAAL armor system will be the first component mapped to the adaptive armor system.

The MAAL system contains three basic components, as shown in Figure 5. The MAAL strand disruptor consists of either the band or link strand (bike chain or similar structured material), which is hanging in tension. This strand through its structure must passively deflect upon threat impact and absorb the threat energy through spallation, fragmentation, and plastic deformation. Structurally, the MAAL air gap

TABLE 1 Adaptive armor design considerations

Adaptive armor design considerations	
ADC 1	The adaptive armor design must be able to prevent the penetrations of 0.30-cal APM2 threats at the threshold and mode one (internal reconfiguration) and adaptive mode two 0.50-cal APM2 threats at objective levels through adaptive (external reconfiguration) at 50% reduction of weight from a fixed RHA armor system.
ADC 2	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.
ADC 3	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.

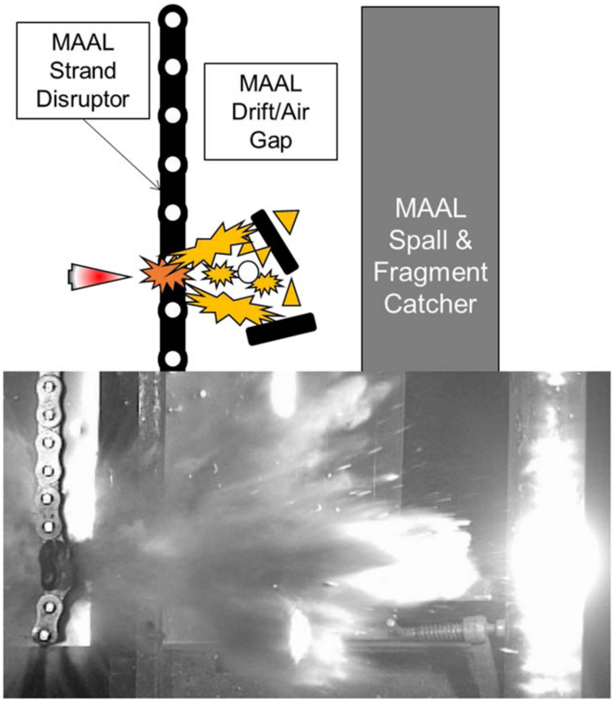


FIGURE 5 Mechanical adaptive armor linkage system structure

provides the disrupted MAAL strand and threat particles volume to disperse and expand. This can be composed of air or any low-density material, such as Styrofoam, for example. The MAAL spall and fragment catcher serves structurally as a dispersed particle catcher, absorbing all residual energy through inertial transfer from the disrupted and dispersed MAAL and threat particles. When the threat strikes the MAAL strand disruptor, projectile energy is absorbed in the fracture of the MAAL strand into fragments. This disruption also causes the threat projectile to yaw, pitch, and tumble, which in turn decreases its energy and penetration. The air gap allows this disruption to take effect. The greater the air gap, the greater the disruption. The air gap also disperses the residual MAAL fragments and threat particles, dispersing their energetic impact over a greater area on the fragment catcher. The high-speed photograph at the bottom of the figure clearly shows the disruption, dispersion, and impact of the MAAL and threat interaction.

3.2 | Mapping MAAL to the mass adaptive factor

Mass is the most influential of the adaptive factors. Mass adaptation can occur through both external and internal reconfiguration modes of adaptability. External reconfigurations of mass include the progressive scaling and redundant scaling of the strand mass. The internal reconfiguration of the mass strand occurs through reallocation. Progressive and redundant mass scaling component mapping is simple because they both are developed from components designed for the dynamic state adaptations. Changing the size of the MAAL strand changes the mass and ballistic performance of the strand. The strands inertial properties and dynamic state also change. The MAAL strand adaptor serves as the same component used for enabling the progressive scaling adaptation. Redundant scaling is a bit different. Redundant scaling is achieved by adding the same-sized strand to the existing strand. For example, if an armor system employs a smaller MAAL strand but needs additional ballistic performance for new threats, adding another same size strand would be considered a redundant scaling of the mass for the armor system.

Mass reallocation component mapping requires pulling the same factor resources from elsewhere in the system to apply them toward the disrupted functional requirement. For an adaptive armor, this would require pulling armor mass that is not ballistically engaged elsewhere in or on the vehicle armor system and applying it where the armor is failing to meet the requirement. Implementing this goal with armor has been previously unachievable because armors have been structurally fixed and therefore not moveable. Even if armor could be moved, no effective method existed to move such a heavy mass in an operationally relevant fashion. This movement could be achieved in an externally reconfigurable fashion; however, this would not make sense because this would create vulnerability in the armor protection that would require another external reconfiguration to fix. The key component in a MAAL armor system is the strand. The strand, whether a belt or linkage, is designed to move at very high speeds. If a MAAL strand was held at one end vertically in the air and then lowered to the ground, the linkages would pile up on top of each other, accumulating mass in that pile, as shown in Figure 6.[9]

This aspect of the links structure can be harnessed as a way to manipulate the mass of the armor. Components to achieve this adaptation include sprockets and idler wheels, a drive sprocket, and MAAL collection bin. 6shows conceptually how these components would work to achieve the enhanced ballistic protection state needed for the system to achieve adaptive resilience state.

3.3 | Mapping components to the dimensionality adaptive factor

Manipulating the dimensionality of the armor system is the easiest and most obvious of the three adaptive factors. The benefits of this

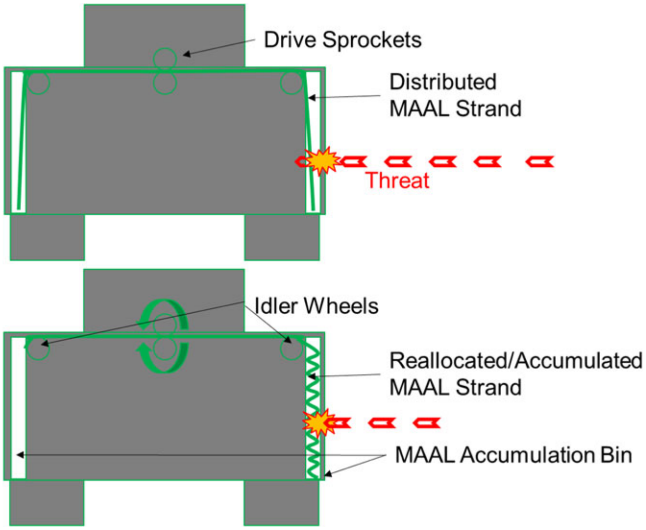


FIGURE 6 Operational view of MAAL strand mass accumulation

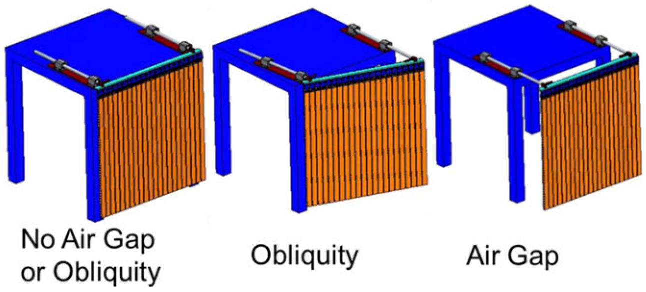


FIGURE 7 Armor dimensionality states
The three images show the initial design for achieving the obliquity and air gap adaptive factor configurations. The far left image shows the adaptive resilient armor system in its least-protected state, which also allows the mobility and strategic transportability requirements for the armor's host platform to be met. The middle and far right images show the enhanced protective states that achieve the protection requirements for the host platform

adaptation were shown through the armor air gap and the obliquity phenomena. Components that enable this must be able to create the armor air gaps and obliquities that provide the needed adaptive capacity and fall within the requirements associated with the adaptive design consideration.

The components that achieve the air gap and obliquities must also be able to measure the weight they add to the armor system. They must have the agility appropriate to manipulate the armor and the structural rigidity necessary to support the armor, yet be lightweight enough to realize the benefits of the obliquity and air gap. This can be achieved using a lightweight actuator and structural linear bearings and shafts, which can both move and support the load of the MAAL armor. Figures 7 and 8 show representations of these components. Some components will need to be designed and fabricated because they do not exist. This is a given for any technology integration: Some components exist, and others must be created to suit the required purpose. The dimensionality components provide a sampling of both, created and available components. The actuator/bearing shaft coupler had to be created specifically for this purpose. This component brought together the driving force of the actuator and the structural rigidity of the linear bearing and shaft. These components enable the armor system to extend and collapse, thus creating the enhanced ballistic protection needed to achieve the adaptive resilience state.

Once the mapping of requirements to physical components is complete, the component performance at the various factor levels must be integrated, verified, and validated to confirm the predicted outcomes found in the characterization-model validation and verification. The components mapped in this phase of the methodology will enable the achievement of the adaptive design points that make this armor adaptive resilient. Although many components lead to the adaptive resilient armor, only key components were discussed to keep the focus on the salient aspects of this step of the methodology. The dynamic state adaptive factor was mapped to the MAAL armor, which can be readily changed and scaled through the use of an interface adaptor bracket. The mass adaptive factor was achieved through accumulation of MAAL where the armor protection is needed. This was achieved through the use of drive sprockets, idler wheels, and the accumulation bin. The dimensionality factor was mapped to structure components such as a linear bearing. These components all enabled adaptive resilience to be realized in the armor system.

3.4 | Ballistic experiment overview

The ballistic characterization of the mechanically MAAL armor regarding the adaptive factor configurations was conducted in accordance with standard ballistic test procedures. The ballistic experiments were conducted at the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) Ground System Survivability (GSS) Survivability Armor Ballistic Laboratory (SABL). This facility is an ISO 17025 certified laboratory and is the Department of Defense's authority and primary test center for the automotive tank purchase description (ATPD) 2352 for transparent armors.

The ballistic range setup is shown in Figure 9. The range was fitted with a high-precision gun. This gun was mounted on a 1000-lb base and had a modular breach that could accommodate all small, medium, and select large caliber barrels and munitions. The range used a chronograph to capture the ballistic velocity of the fired projectiles. After the chronograph, a break screen was set up, which triggered the top and side high-speed cameras to film the terminal ballistic event. The high-speed cameras were capable of capturing thousands of frames per second. These special cameras were mounted on both the top and side of the target chamber. For this test setup, recording the velocity after the MAAL impact was desired in order to calculate the residual projectile kinetic energy. A standard rule was used to measure the disrupted projectile particle velocities after the MAAL impact.

The targets for this ballistic characterization were the only nonstandard items. The first target was the MAAL strand. This was the primary adaptive component of the adaptive resilient armor system. This component was manipulated, scaled, and otherwise adapted between each shot. The second target consisted of a semi-infinite series 0.5 inch plates of 6061-T651 aluminum. Semi-infinite means that the end or edge effects of the target were designed to have no effect on the ballistic performance. This target setup allowed the MAAL to disrupt the

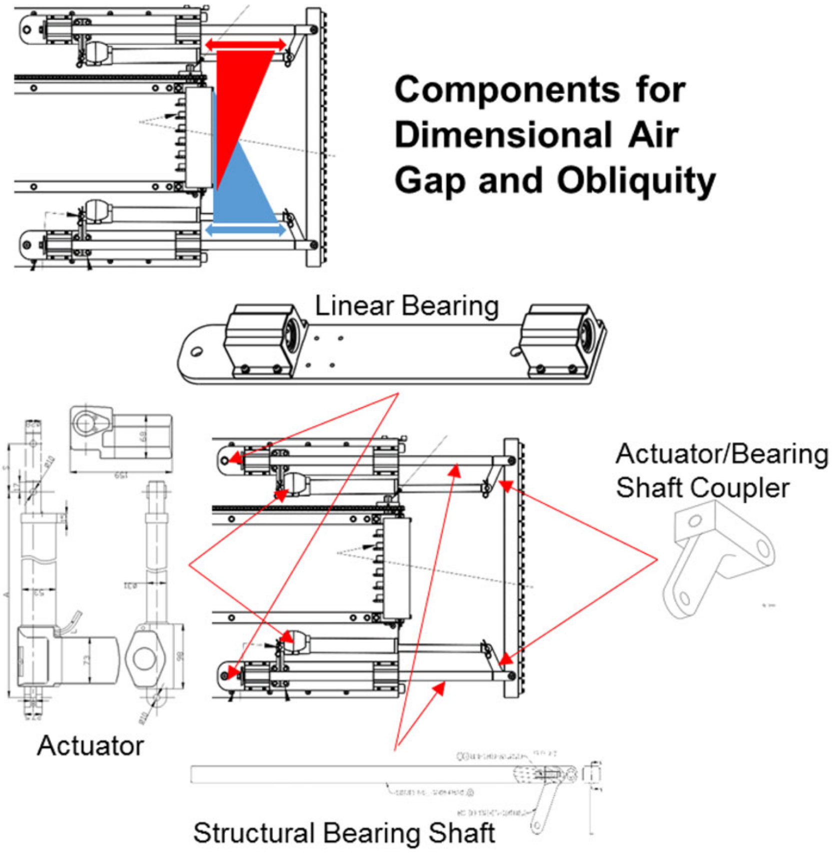


FIGURE 8 Armor dimensionality components This figure depicts the components mapped to achieve the air gap and obliquity adaptive factor configurations. The linear bearing, structural bearing shaft, and the actuator/bearing shaft coupler provide mobile structural support for the adaptive armor weight. The actuator provides motive force to the shaft to enable the internal reconfigurations to occur.

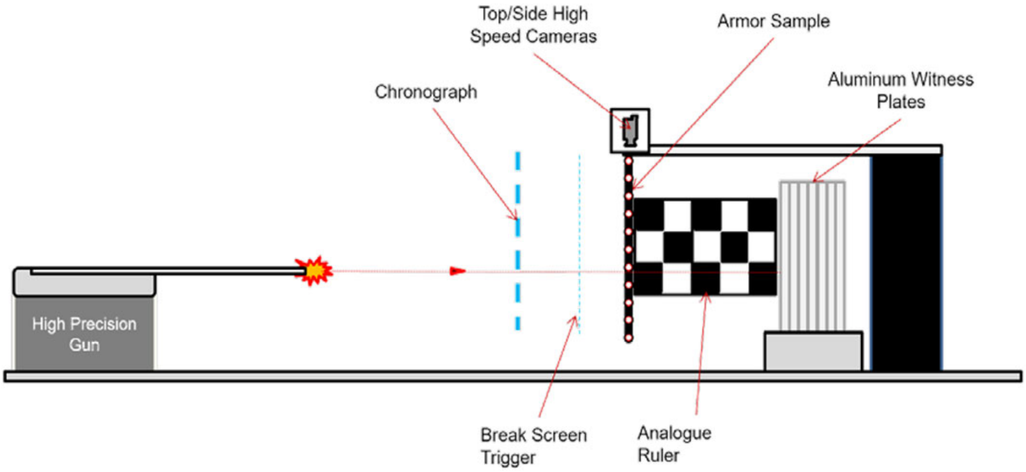


FIGURE 9 Ballistic test range setup

threat projectile, the cameras to witness and record the disruption, the rule to capture the residual velocity, and the softer aluminum to measure the residual penetration of the disrupted projectiles.

During the experiments, the MAAL was placed at the specific point of design interest, and the threat projectile of interest was fired at the series of targets. The projectile struck the MAAL strand, and the residual armor and projectile particles embedded in the aluminum witness plates. A less-protective adaptive design configuration resulted in a residual impact several plates deep, and a more-protective design configuration resulted in a shallow surface impact. The plate in which the most deeply penetrating projectile particle terminated was the plate counted in the total areal density of the target. This is shown in Figure 10.

An impact was regarded as a complete penetration (CP) or failure if the projectile or a resulting target fragment from impact created a hole in the witness plate through which light could be observed after removing the projectile. If an impact did not result in a CP, it was considered a partial penetration (PP), or win. From Figure 10, the number in the lower right corner depicts the 0.5-inch aluminum plate order. As shown, the plates have penetration holes. Plates 4, 5, and

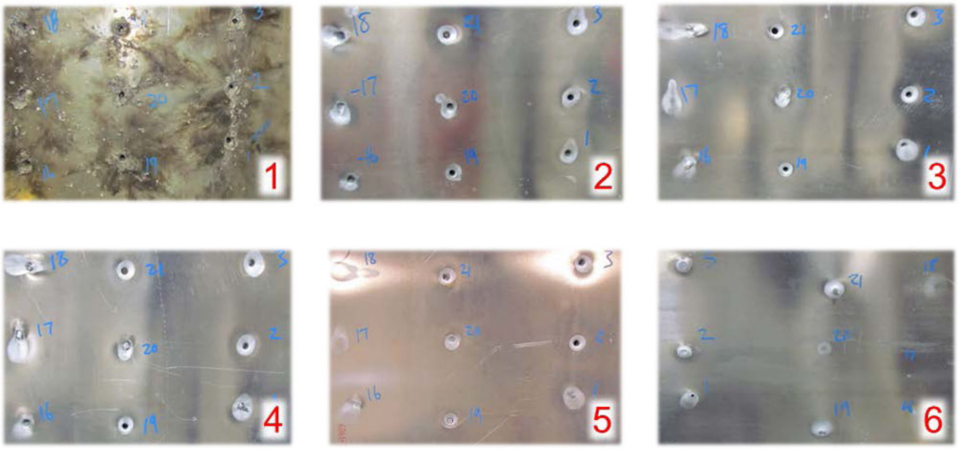
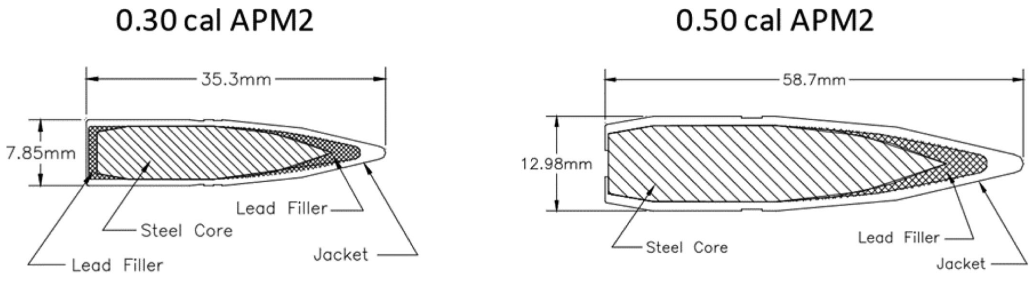


FIGURE 10 6061 T651 aluminum witness pack



Projectile Type	Projectile			Core		
	Length (mm)	Diameter (mm)	Weight (g)	Length (mm)	Diameter (mm)	Weight (g)
0.30-cal. APM2	35.3	7.85	10.8	27.4	6.2	5.3
0.50-cal. APM2	58.7	12.98	45.9	47.5	10.9	25.9

FIGURE 11 Dimensional and mass characteristics for 0.30-cal APM2 and 0.50-cal APM2.
Source: Gallardy.[8]

6 show projectile terminations. If the projectile terminated in plate 4, the areal density of the MAAL strand plus four aluminum witness plates would be counted in that experiment's terminal areal density. It can be seen across the stack of plates that shot 17 penetrated and terminated in the plate 3 (least), whereas shot 21 penetrated and terminated in plate 6 (most).

The U.S. 0.30-cal APM2 and 0.50-cal APM2 were used in this study. These projectiles are shown in Figure 11. The APM2 projectiles have hardened steel cores with hardness of Rockwell C61-63. These projectiles were used because a large body of armor characterization results has used these threat projectiles, and also because this was the notional threat used in the MSIAR case study. The first series of experiments were conducted with the 0.30-cal APM2. After a large battery of experiments, it became evident that the MAAL armor system was potent in terminating these threat projectiles. This was a good result, but unfortunately unhelpful for the purpose of these ballistic experiments. The structure of the catcher phase of the adaptive resilient MAAL armor system was intended to show how each adaptive factor configuration contributed to the ballistic protection of the armor. The majority of the 0.30-cal experiments resulted in splash impacts on the first (front) aluminum plate of the catcher phase. The intention was for these penetrations to occur five or six plates deep and then reduce as the armor system was adapted. The MAAL armor system worked so well that the adaptation configuration effects were indiscernible. After the result, the threat projectile was scaled to 0.50-cal APM2, which was much better suited for the purpose of these research experiments.

3.5 | Ballistic experiment results

The ballistic characterization conducted in support of this research served as an abbreviated form of the two verification and validation steps of the MSIAR. These experiments not only served as the verification and validation steps of the methodology, but also affirmed the efficacy of the methodology in realizing the adaptive resilience attribute in technological systems. The adaptive resilient armor demonstrator and the ballistic characterization served as the proof of concept for this methodology—if followed, significant functional benefit can be achieved. For an armor system, that benefit is realized in an armor system that can terminate threats at lighter areal densities. The ballistic results of these experiments are compared to standard armor steel plate because that is the benchmark against which all ballistic armor is compared. Throughout these plots, a magenta diamond depicts a

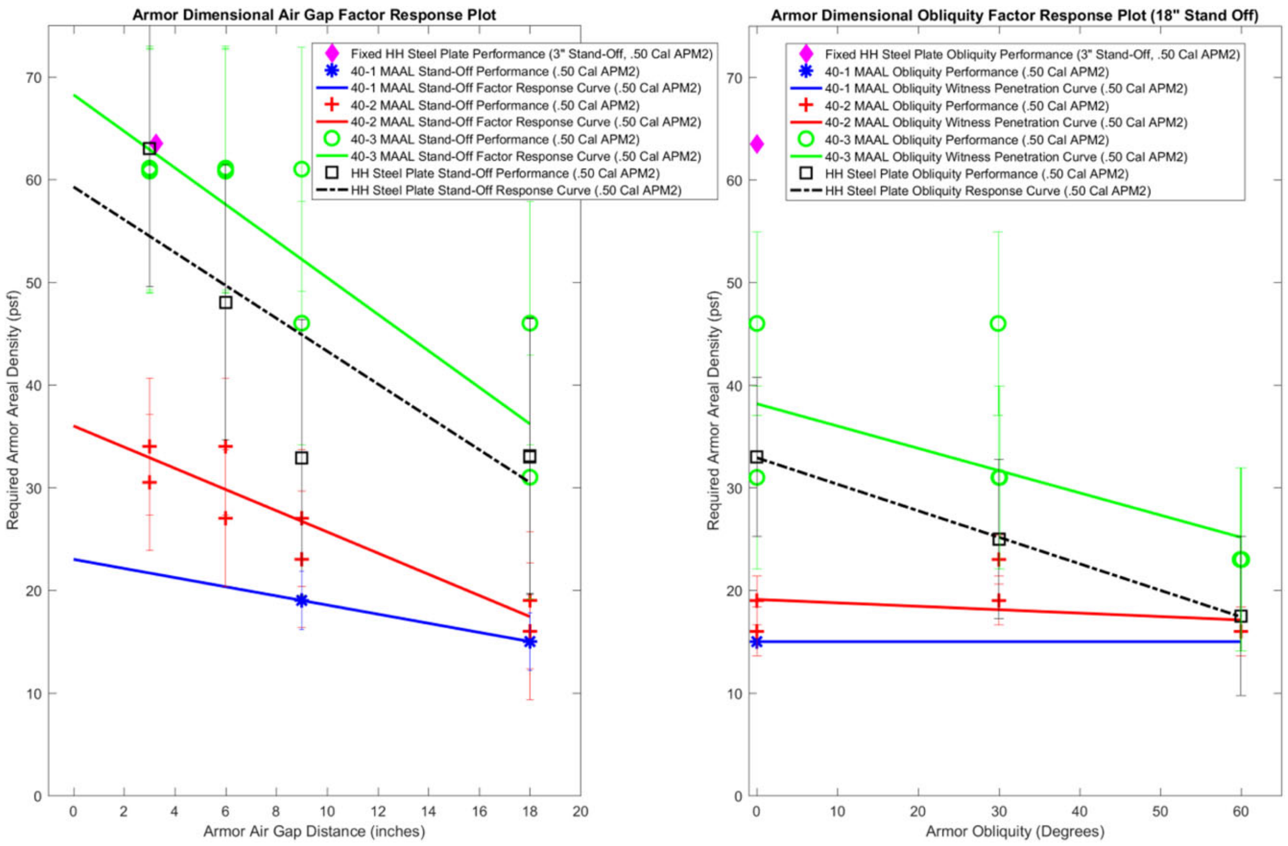


FIGURE 12 MAAL ballistic evaluation plots

TABLE 2 MSIAR results in addressing the adaptive design considerations

Adaptive armor design constraints		Results
ADC 1	The adaptive armor design must be able to prevent the penetrations of 0.30-cal APM2 threats at the threshold and 0.50-cal APM2 threats at objective levels through adaptive mode one (internal reconfiguration) and adaptive mode two (external reconfiguration) at 50% reduction of weight from a fixed RHA armor system. (T: 24 psf; O: 40 psf)	Objective threat defeated at 16 psf.
ADC 2	The adaptive armor design must achieve the maximum amount of ballistic protection from the least amount of weight.	See above. National objective threat defeated at 80% reduction in areal density from fixed armor system.
ADC 3	The integrated adaptive resilient armor design while integrated on the host GCV platform may not exceed 204 inches of total GCV system width during strategic transport.	Prototype system buys back 36 inch of total vehicle width.

similar structured and mass fixed armor design made of MIL-DTL-41600E high hardness steel. This demonstrator physically achieved all requirements and adaptive design considerations, as well as all the adaptive factor configurations generated by the methodology. These configurations provided enhanced ballistic protection capability over a traditionally designed armor with similar material technology through adaptive internal and external design reconfigurations. Further, the adaptive resilient armor demonstrator showed how in certain circumstances, the methodology can eliminate the need to compromise on certain system components constrained by competing requirements. The outcomes of the design study are depicted in Table 2.

Ballistic evaluation of the adaptive component configurations demonstrated significant enhancement to the ballistic protection of the armor system. In some instances, ballistic protection against objective threats attained an 80% reduction in armor system weight over a nonadaptive resilient armor system. Nonadaptive armor systems can perform at this weight but with significant operational consequences for the width of the vehicle system on which the armor was integrated. The adaptive resilient armor system can achieve this enhanced protection at a lighter weight while retaining the adaptive ability to collapse the enabling width, regaining the narrow width for mobility when needed. This is shown in the ballistic evaluation results shown in Figure 12.

These plots depict the core proof of concept ballistic experiments for the MAAL armor at key adaptive factor configurations. These plots show the performance at key dimensionality adaptive factor configurations. The bright pink diamond depicts the performance of a similar nonadaptive static armor. It does not have a range of performance because it does not have adaptive capacity needed to provide the range. The adaptive resilient armor can adapt its armor dimensionality and obliquity to provide objective threat protection at an armor areal density 50 pounds per square foot (psf) less than the fixed nonadaptive armor. This weight can be used to regain vehicle performance with respect to mobility and transportability.

4 | CONCLUSIONS AND FUTURE WORK

The methodology for the system integration of adaptive resilience is shown to be a sound methodology for the creation of adaptive capacity within armor technological systems. The MSIAR enables these systems to adapt performance factors and realize a resilient state of operation for complex environments. This methodology was applied to the design of an adaptive resilient armor system. This system was based on relevant operational requirements in which a top-level function was defined by a requirement often at odds with other critical requirements for the greater system of systems. The adaptive capacity realized in the adaptive resilient armor system provided the armor system the capability to meet and exceed top-level functional requirements in a fashion that did not implicate other requirements. The armor system provided a range of ballistic protection that handily met the requirements, and had extensible means available to rapidly address unknown/emerging penetrating threats.

This research serves as an initial foray into integrating the attribute of adaptive resilience into a technological system. The proposed methodology incorporated concepts and principles from the maturing field of resilience engineering and merged them with systems design and engineering principles. This methodology was demonstrated on a single-case case study of the design of an adaptive resilient armor system, although it is meant for any technological system that operates in a complex operating environment and with competing requirements. Future research efforts for the methodology should center on applying the methodology to other systems that require adaptive resilience as a functional attribute. This future research should focus on refining the activities and processes associated with each step of the methodology.

This methodology makes possible many new applications for integrating adaptive resilience technological systems. These questions and many more will arise as systems engineers and designers employ and expand this approach. Adherence to the fundamental principles of system engineering will serve as a guidepost in answering these complex questions. The methodology for the system integration of adaptive resilience has the potential to eliminate many of the system tradeoffs that have limited the functional utility of systems that operate in complex operating environments. The methodology also has the potential to enhance the operational effectiveness of systems that continually encounter operational challenges that stress or overmatch their ability to maintain top-level functionality. With proper discipline and application, this methodology enables users to enhance significantly the resilience of the systems they design.

REFERENCES

1. Cannon J. *Methodology for the system integration of adaptive resilience in armor*. Ph.D. Dissertation, Department of Systems Engineering, Naval Postgraduate School; September, 2016.
2. Jackson S. *Architecting Resilient Systems: Accident Avoidance and Survival and Recovery from Disruptions*. Hoboken, NJ: John Wiley & Sons; 2009.
3. Suh NP, Crookall JR. *The Principles of Design*. Shaw MC, ed. Oxford, UK: Oxford University Press; 1990.
4. Buede DM. *The Engineering Design of Systems: Models and Methods*, 2nd ed. Hoboken, NJ: John Wiley & Sons; 2009.
5. McKenney T, Kemink L, Singer D. Adapting to changes in design requirements using set-based design. *Naval Eng J*. 2011;3:67–77.
6. Beery P. A model based system engineering methodology for employing architecture in system analysis: developing simulation models using system modeling language products to link architecture and analysis. Naval Postgraduate School, Defense Technical Information Center; 2016.
7. MacCalman A, Beery P, Paulo E. A systems design exploration approach that illuminates tradespaces using statistical experimental designs. *Syst Eng*. 2016;19(5):409–421.
8. Gallardy DB. Ballistic evaluation of 6055 aluminum. Army Research Laboratory Publication ARL-MR-0904, Army Research Laboratory, APG, MD: 1–12; 2015.
9. Cannon J. U.S. Army. Mechanically adaptive armor linkage. US patent 2017/0097211 A1; April 6, 2017.

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