Resilience for Space Systems: Concepts, Tools and Approaches

The U.S. space community recognizes that the operational environment of space is changing. America no longer holds a monopoly on space technology. The only certainty is that America must navigate a future increasingly crowded with friendly, hostile, and new players challenging it for strength. This shift has brought about an increase in threats directed at the space domain and supporting infrastructure.[1] Space and ground system architectures must maintain a high degree of resilience to ensure mission success. Resilience should be treated as an important design consideration during decision-making to be traded along with cost and capability.[2] Consequently, a taxonomy has been designed to facilitate discussions about resilience concepts and threat mitigation scenarios.

Resilience is not consistently defined across the space community. Here, resilience is defined as the ability to deliver the mission in the face of manmade or natural interference. Based on that definition, The Aerospace Corporation (Aerospace) has developed a taxonomy that looks at the entire lifecycle of a system with respect to its ability to meet mission requirements. The taxonomy is a framework that can adapt to new situations as new threats and potential countermeasures emerge (see Figure 1). The options in this taxonomy are infinite, facilitating innovative ideas that cross mission domains. Aerospace maintains a growing, flexible dictionary, expanding the degree and availability of analysis that can be tailored at the mission, system, or program level. This allows the taxonomy to stay current and relevant as new threats emerge and new technology is developed. Figure 1 shows a sample of the taxonomy; a full dictionary will be available in the Aerospace TOR-2017-02693.[3]

The formal taxonomy structure defines a trade space for resilience that includes mission requirements, threats, strategies, actions, enablers, system and architecture resilience needs, and metrics.

- **Mission requirements** outline what must be accomplished for a particular mission, such as warfighter or intelligence gathering needs.
- **Threats** to missions supported by space systems emerge almost daily. These include manmade and natural hazards external to the system, all of which may, intentionally or unintentionally, compromise a particular mission.
- **Strategies** are the concepts implemented to address real or perceived future *threats*. They are a plan, method, or series of maneuvers or stratagems for obtaining a specific goal or result.
- **Actions** implement *strategies*. Some *actions* have precursor or successor actions—for example, a

threat must be detected before it can be identified. *Actions* are typically constrained by time.

- **Enablers** represent the physical entities needed to perform specific *actions*. They are the people, tools, hardware, software, and infrastructure associated with the mission.

- **System and Architecture Resilience Needs (SARNs)** emerge as a result of identifying the *enablers*. These needs may require changes to a design or concept of operations to ensure that action can be taken by the enabler when a strategy is implemented to mitigate a threat. SARNs may apply at different levels, for example segment level or system-of-systems level.

- **Metrics** are tools to quantify the components of the taxonomy. They provide quantifiable, testable, and achievable system requirements, which include the needed level of resolution, such as the minimum bandwidth of a network.

Resiliency Across the Community

Mission requirements and objectives must be clearly defined before mission *threats* can be

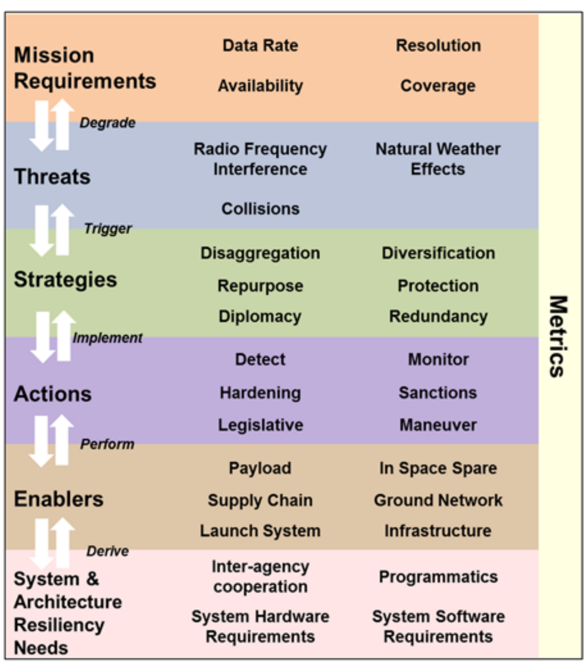

Figure 1: Resiliency Taxonomy Overview

fully understood and considered for all customers in the community. At a high level, this taxonomy structure covers any US space assets that need resilient solutions. Each member of the community has a different charter and objective, and each has a need to protect its space assets from intentional or unintentional harm in order to complete the mission at hand. The Defense Department's mission is to provide the military forces needed to deter war and maintain the security of the country. The intelligence community's mission focuses on foreign relations. Civil organizations vary, but can focus on pioneering space exploration and scientific discovery, as in the case of NASA, or understanding weather and atmospheric conditions, like NOAA. The commercial sector pursues a variety of missions.

Each member of the community favors different *strategies*, *actions*, and *enablers* depending on mission needs and organization charters. This taxonomy accounts for mission, operational, and acquisition perspectives and highlights the breadth of resilience options to satisfy community needs. It is intentionally organization agnostic and mission independent.

Resilience at the Mission and Functional Level

Once *mission requirements* are identified, along with mission essential functions, *threats* that may impact that mission can be identified, and possible *strategies* can be analyzed. A strategy is a means of achieving a goal—so it is important to identify the objectives with regard to the threat. For example, if the goal is to avoid the *threat* of a vehicle collision, then the *strategies* will coalesce around preventive, rather than responsive, measures.

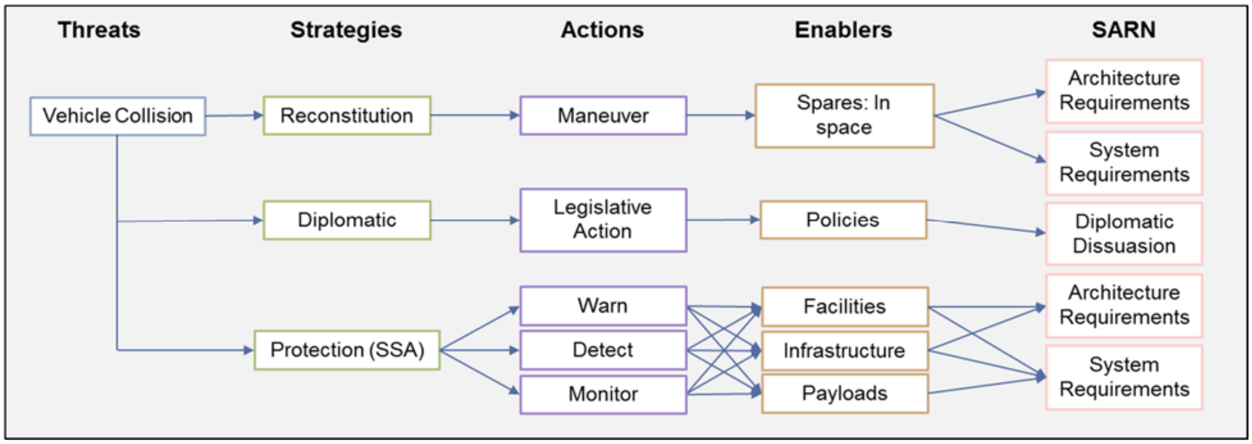

Figure 2: Taxonomy Use Case

Facilitating *Actions*, *Enablers* and *System and Architecture Resiliency Needs* through the taxonomy provides a systematic way to structure analysis that is repeatable and through, relying on both the overall community of knowledge and human-in-the-loop Subject Matter Expert Analysis.

The application of the taxonomy allows us to think through "out of the box" solutions which may not have otherwise been considered by developing multiple **mitigating scenarios** based on the dictionary. Further analyses will then help define the nature of those preventive measures. For example, does the system have to retain 100% capability, or can it operate in a functionality reduced safe mode? What is the nominal capability versus contingent capability? What is the political environment of the scenario? Is this scenario within my program's control?

For example, Figure 2 illustrates a threat, similar to the Iridium 33 collision with the Kosmos 2251 vehicle in 2009. Though there were many responses to this *threat*, post collision Iridium chose to implement a *strategy* of reconstitution, as shown in the first possible pathway, by performing the *action* of maneuvering the *enabler*, an in-space spare. As a result, within a few weeks all services were restored.

Alternatively, they could have done a number of different things up front to address this threat. The taxonomy helps us to identify those additional responses through the use of **mitigation scenarios**. The second strategy, an alternative to an expensive on-orbit spare, diplomacy, reflects a preventative resilient measure rather than a reactionary measure. A diplomatic strategy entails taking the necessary legislative *actions* which, if implemented by the appropriate national and/or international law enforcement, can make a system more resilient by leveraging fear of economic sanctions or other repercussions. This underscores the need for *enablers*, in this case the appropriate policies, to ensure that there will be consequences for interfering with another mission. If properly enforced, these laws may have helped prevent this collision by deterring negligence or aggression.

Many other possible *strategies* exist for this use case, though only three were selected for purposes of this illustration. In the first two cases shown, the taxonomy follows a linear and single path. The other cases show that several *actions* and/or *enablers* may be necessary in order to complete a given strategy. Figure 2 represents possible options for countering the *threat* of a vehicle collision – highlighting how to use the taxonomy to build alternative mitigation

Table 1: Excerpt of Iridium Example Resiliency Mitigation Scenarios

Strategy	Action	Enabler	Mitigation Scenario	Lifecycle Stage	Within Program Control	Results in acceptable consequence
Reconstitution	Maneuver	In Space Spare	In flight replacement	Post Collision	Yes	No
Diplomatic	Legislative	Policy	Diplomatic Discussions	Preventative	No	Yes
Protection	Warn, Detect Monitor	Ground Systems	Increase Warning Time	System Design	Yes	Yes
Protection	Hardening	Shielding	Shield Hardening	Satellite Design	Yes	Yes
Defensive	Maneuver	Propulsion System	Reactive Maneuver	Impending Collision	Yes	Yes
Reconstitution	Launch on Demand	Ground Spare	Launch Spare	Post Collision	Yes	No

scenarios (shown in Table 1). This exercise can be done from the perspective of a single segment, or from the perspective of an entire enterprise.

As this vehicle collision example shows, the taxonomy facilitates the brainstorming process, identifies gaps and unknowns that can then help generate system requirements. The taxonomy is a tool that can help planners think through the risks in a deliberate, structured way. It directs the thought process concerning which strategies to employ and which resources to apply to develop a mitigation scenario as shown in Table 1. Once a mitigation scenario has been developed, the program can start to understand the lifecycle stage in which it can be implemented, the organization that would be responsible for implementing it, and the outcome of its implementation. If the mitigation scenario is within the program area of responsibility, and it results in an acceptable outcome, additional efforts can focus on creating resilience requirements tailored to the program mission and feasible threats the program could encounter.

Additional work is underway to continue developing and honing these processes to ensure their applicability across the community. Quantifying the probability of threats and their impacts along with assessing the most effective mitigation scenario for each threat is an important next step in this process. Aerospace is continuing to explore these next steps, some of which are explained in depth in the upcoming TOR-2017-02693.[3]

Addressing the Challenges

Resilience is one way to help address mission assurance concerns. Aerospace has been helping the government achieve mission success through mission assurance for more than 50 years. The taxonomy described here is one method of systematically approaching the topic of resiliency that could benefit all members of the space community. The concise methodology to explore resiliency options and develop mitigation scenarios will help mission assurance processes promote innovative approaches to meeting resilience requirements.

References

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