2013 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SYSTEMS ENGINEERING (SE) MINI-SYMPOSIUM
AUGUST 21-22, 2013 – TROY, MICHIGAN

APPLICATION OF INTEGRATION READINESS LEVEL IN ASSESSING TECHNOLOGY INTEGRATION RISKS IN A DOD ACQUISITION PROGRAM

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ABSTRACT

Integration risk differentiates from other program risk in that it always involves interfaces between various systems or subsystems. The level of integration required is different depending on the phase of the Acquisition Life Cycle (i.e. Materiel Solution Analysis Phase, Technology Development Phase, Engineering and Manufacturing Development Phase, Production and Deployment Phase and Operation and Support Phase).

This paper focuses on the process used to assess the integration risks of integrating various technologies or subsystems into a vehicle platform. The process presented provides a step by step instruction on how to perform an integration risk assessment.

A new Integration Readiness Level (IRL) rating system has been developed by the TARDEC System Engineering and Integration Group to help acquisition vehicle programs as well as science and technology teams to evaluate the health of their technology or subsystem integration into their vehicles. The rating system is applicable to all phases of the program life cycle. Some of the key processes/tools for integration referenced in the IRL Table are discussed to better understand how the integration assessment can be performed.

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INTRODUCTION

System integration is a significant systems engineering discipline. It is one of the most time-consuming activities in the systems engineering process. Depending on which phase of the program life cycle, the system integration tasks are not the same. During the early stage of a project, integration means planning out all the processes and activities involving people, facilities, procedures, concept and architecture design, cost, schedule, technology selection, etc. The goal of integration is to make sure all system elements work together so that the project can be completed as planned. During the technology development and design phase, integration means establishing the system architecture and all the interfaces between subsystems. After various subsystems are produced, integration means putting a system together physically and verifying all subsystems work as a whole.

Technology Readiness Level (TRL) methodology [1] has been used extensively to assess technology maturity based on the level of assembly and the environment that it is tested in. The main purpose of using TRL within the Department of Defense (DoD) is to provide program management a tool to assess the level of risk in transitioning a technology to production through the acquisition cycle. Many aspects (requirement analysis, testing, and integration) of technology readiness are currently combined into one metric (TRL). The definition of TRL, however, does not provide any detail on what to evaluate when integrating a technology into a system. Past experience has demonstrated that technologies having a high TRL maturity rating do not necessarily mean lower risk. A mature technology not properly integrated will have significant impact on program success. As a result, even with mature technologies, 25% of DoD acquisition programs (2004-2010) were still reported by the Office of the Secretary of Defense (OSD) to exhibit integration issues resulting in cost and schedule overrun [3]. Major contributors include incomplete architectures, inadequate technical planning, lack of subject matter expertise at the integration level, over estimated technology maturity and stovepipe development with late integration, etc. Therefore, it is not sufficient to ONLY consider the maturity of a technology without considering how it interfaces with other subsystems of the vehicle platform. Unless the TRL description is significantly increased [2] to clarify the implied integration needed to achieve each level of TRL, it is rather confusing for users to establish the risks associated with technology integration by using simply the TRL definitions. According to the Defense Acquisition Guidebook (DAG) [4], to integrate a technology properly, one should focus on the physical architecture, the analysis of the interface relationships and the development of the interface requirements and metrics. These tasks cannot be accomplished by the technology integrator alone. All interface requirements have to be jointly developed with the personnel responsible for the interacting systems. For this reason, instead of using the TRL metric alone to evaluate the level of integration performed, it may be more appropriate to introduce a separate metric (IRL) to evaluate technology integration. A detail comparison between TRL6 and IRL6 is included to demonstrate how the two levels are different (see Table 1).

Recognizing the importance of integration and the lack of integration metric, various DoD organizations have been trying to establish separately the best tool to evaluate a project based on how well the integration processes have been executed. Multiple attempts have been made since 2001 to develop a new IRL and other system engineering checklists to capture the integration risks across the different phases of the acquisition, technology and logistics life cycle. In 2009, the US Army Tank Automotive Research and Development Engineering Center (TARDEC) System Engineering and Integration (SE&I) Group followed DoD Technology Readiness Assessment (TRA) Guidebook to evaluate the technology maturity and technical risks of a particular ground vehicle and found that it was insufficient to use TRL alone to evaluate technology maturity. Based on requirement non-compliance matrix and failure analysis corrective action reports (FACAR), more than 30% of all issues were related to system integration. Consequently, TARDEC SE&I began to collect many research and educational papers related to system integration and integration risk assessment. Using the key findings and combining with industry best practices, SE&I developed a new set of IRL definitions that are different from what have been previously defined [5, 6, 7, 12]. A new column has also been added to the IRL Table to describe the best integration tools/practice/process to be used (see IRL Table in the Reference section) for each level of IRL. These best practices will be briefly explained in this paper. Since 2009, for all TARDEC supported acquisition programs requiring technical risk assessment (TRA) as part of the milestone mandated requirements, both TRL and IRL evaluations have been performed together on all key technologies (CT) for various ground vehicle programs (Stryker, Abrams, Bradley, GCV, AMPV, , RSJPO, etc). From these assessments and detail comparison of various existing IRL definitions, the TARDEC SE&I group revised the IRL definitions so that the IRL metrics are consistent with the TRL definitions. Detail performance specifications associated with each critical technology (CT) have to be established in order to perform TRL assessment objectively. Likewise, the interface requirements have to be established also in order to perform the IRL assessment.

The purpose of this paper is to introduce the new IRL rating system to supplement the current TRL assessment in capturing the overall program integration risks. Some of the key integration methods are further demonstrated graphically with practical examples.

DISCUSSION

All program managers of DoD acquisition programs are required to justify to the Milestone Decision Authority (MDA) during the formal Milestone B Review that the program critical technologies are mature with acceptable risk level. In preparation for the MS-B Review, the work actually starts during the Materiel Solution Analysis Phase (Figure 1) where user needs, system capabilities, system level requirements and solution architecture are being established. During the Technology Development phase, the program team must utilize the system architecture framework to establish all the required integration for all subsystems including all technologies.

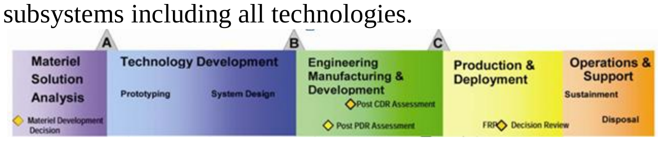

Figure 1 DoD Acquisition Phases & Milestone

According to DAG, "Integration is defined as incorporating lower level system elements into higher level system element in the physical architecture. It involves linking of hardware and software elements. It is analogous to the process of "rolling up" lower level Work Breakdown Structure (WBS) elements into the next higher system/subsystem level". The key questions to consider are:

- Are the interface requirements adequately defined from performing the proper interface analysis? Are they jointly developed with personnel responsible for the interacting systems?
- Does the Interface Control Document (ICD) have all the interface requirements and acceptance criteria specified including all system constraints?
- Are the verification and validation procedures established for these interface requirements?
- Has the program met all interface requirements under all imposed constraints?

Key ingredients for proper integration are:

1. Interface/boundary diagram with all functional and physical interfaces
2. Interface analysis to characterize the nature of the interfaces and system constraints
3. Interface requirements with acceptance criteria
4. System integration test results to verify interface specifications are met

Key design features for integration:

1. Standard interfaces
2. Open architecture
3. Future growth potential
4. Easily adaptable to be used in other systems

TRL 6 is one of the metrics used during Milestone B Review to qualify a technology to be used in a major defense acquisition program. After the prototype system with the integrated technology has demonstrated in a relevant environment, it has to undergo detail engineering design and manufacturing feasibility studies before low rate production can begin. A detail comparison of TRL6 and IRL6 will demonstrate the differences between TRL and IRL metrics.

Bold = Different	TRL=6	IRL=6
Definition	System/subsystem model or prototype demonstration in a relevant environment.	Integration element baseline established.
Description	Representative model or prototype system, which is well beyond that of TRL 5, is **tested in a relevant environment**. Represents a major step up in a technology's demonstrated readiness. Examples include **testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.**	**Platform interfaces** have all been **identified and agreed to.** All enabling/critical technologies / components for the integration CIs have been demonstrated. Preliminary design key characteristics (KC) defined. **Notional interface proposals with constraints have been established** (mechanical, all required vehicle modifications to accept technologies to be integrated, electrical/cabling, wireless protocol, security, human interface etc.). The integrating technologies can **Accept, Translate,** and Structure Information for its intended application.
Questions to Consider	**Has the engineering feasibility been fully demonstrated?** (a) **System** requirements finalized (reliability, technical, etc)? (b) Operating environment defined? Has a representative model / prototype been tested in a high-fidelity lab or simulated operational environment? (a) **Relevant environment** defined? (b) Tested at relevant environment? (c) What is the margin of safety, test to failure, sensitivity (robustness)? Has M&S been used to simulate system performance in an operational environment? **(a) M&S and test correlation?**	Have individual systems been tested to verify that the system components work together? Have integrated system demonstrations been successfully completed? **External interfaces established** (hardware, software, physical interfaces, and functional interfaces)? **Interface analysis completed?** **Test** requirements **of interfacing systems and acceptance criteria?** Met all **interfacing requirements** by tests or analysis (systems work together)?

Table 1 TRL6 and IRL6 Comparison

A system prototype has to be tested in a relevant environment to satisfy the TRL 6 exit criteria. The intent is to uncover any failure modes associated with the technology during system testing and to verify if the system meets the performance requirements that it is designed to do. In preparation for the testing, the technology has to be integrated into a representative system prototype or simulated vehicle platform. The exit criteria of IRL 6 are to establish the technology functional and physical interfaces with the interacting subsystems or systems under environmental and system constraints and to demonstrate that these interface requirements are met. Each interface can have many interface requirements with corresponding measureable acceptance criteria. These requirements can be directional such as regulatory and environmental constraints or bi-directional where one subsystem is requiring of or requiring by another interfacing subsystem to meet certain criteria. For all bi-directional requirements, the interface criteria have to be established and agreed to between functional and physical interacting systems by performing an interface analysis (Table 1). The first step in performing an interface analysis is to create a specific interface/boundary diagram from a generic interface/boundary diagram template as depicted in Figure 2. An interface/boundary diagram is a graphical illustration of the relationships between the technology and its surrounding components, subsystems, and systems within a vehicle platform, its functional interfaces, and all associated regulatory and environmental constraints. All interface/boundary diagrams have to be developed jointly between the technology integrator and the interacting subsystem/system owners. An interface diagram can be drawn to any level of detail with the following features showing:

1. Important functional and physical interfaces
2. How the elements interact with each other internally
3. How the elements interact with the external systems

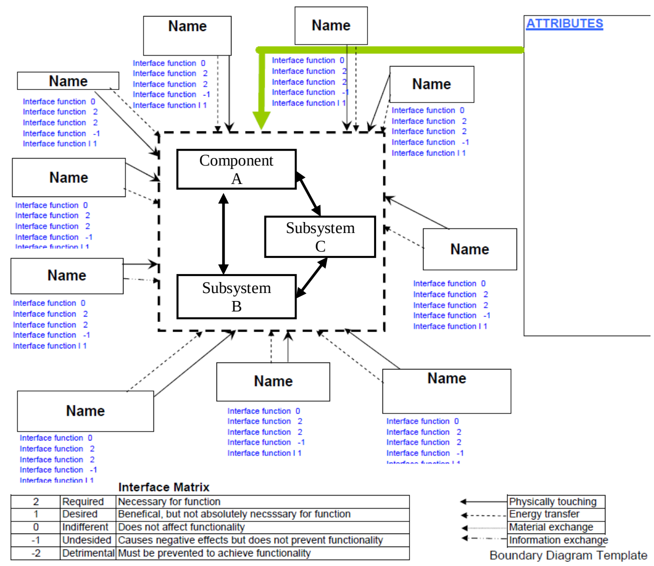

Figure 2 Interface/Boundary Diagram Template

As shown in the boundary diagram template (Figure 2), each interface can have multiple interface requirements. An example of a generic automotive suspension system interface/boundary diagram is shown below.

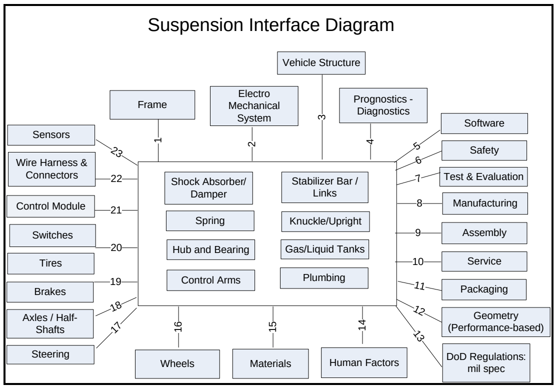

Figure 3 Generic Suspension System Boundary Diagram

The second step to perform an interface analysis is to characterize each interface with the appropriate physical and functional requirements. The following interface types and attributes in Table 3 can be used to establish the measureable acceptance criteria for each requirement.

Interf No.	Reqt ID	Interface Type	Interface Attributes	Target	Tolerance	Unit	Importance	Concur
		Mechanical	Physical				Required	Yes/No
		Electrical	Energy Exchange				Desired	
		Electromagnetic	Info Exchange				Indifferent	
		Thermal	Material Exchange				Undesired	
		Communicate					Detrimental	
		Fluid						
		Computer						

Table 2 Interface Analysis

The attributes for each interface can be:

1. Physical: relative position or movement between two components.
2. Energy exchange: an energy flow, force or electrical power between components.
~~3.~~ Information exchange: information transmitted between components.
4. Material exchange: Material flow between components.

Description of interfaces:
1. Mechanical interfaces – size, weight, package clearance.
2. Electrical interfaces – connectors, cables, energy storage, power generator, controls.
3. Electromagnetic interfaces – magnetic fields, radio and optical links, etc.
4. Thermal interfaces – heat production, dissipation, air conditioning heat transfer, etc.
5. Communication interfaces – analog and digital signals telecommunications, transmission, etc.
6. Fluid interfaces – air conditioning working fluid, compressed air, exhaust gas, lubricating oil, fuel, etc.
7. Computer interfaces – hardware/software, protocol, users, peripheral, etc.

In addition to the interface requirements, key performance requirements of a technology or subsystem shall also be established. They can be developed from the Capability Development Document (CDD), Operational Requirement Document (ORD), System Performance Specifications (PD), Subsystem Performance Specification, etc. Typical vehicle platform system requirements can be illustrated in a functional requirement tree as shown in Figure 4. Establish the technology performance requirements by selecting the system requirements that are relevant to the specific technology/subsystem. Each requirement shall have verification method and acceptance criteria. State any assumptions made to support the use of data from equivalent or representative technology prototypes such as relevant environments and mission profiles. Trace all requirements to top level user capability needs.

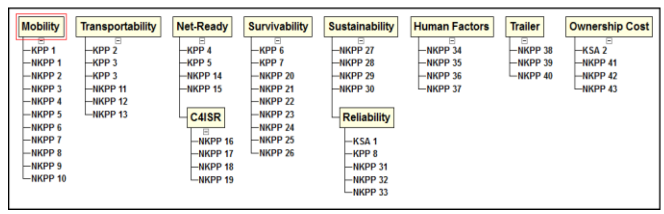

Figure 4 Functional Requirement Tree

The purpose of using various readiness levels (technology, integration and manufacturing) is to determine if an integrated technology can meet all of the system functions within an acceptable level of risk.

Technology risks can be either quantitative or qualitative [10]. To identify the quantitative risks, having a complete set of requirements (Table 3) specific to the technology is necessary. Risks arise when the integrated system has the potential of failing any of the requirements either through physical testing or modeling and simulation.

Quantitative Risks	Description	Acceptance Criteria	Verification Methods	Result	Risk	Consequence	Likelihood	Mitigation
System Requirements								
Subsystem Requirements								
Interface Requirements								
Manufacturing Requirements								

Table 3 Quantitative Requirements

A routine procedure to capture potential integration risks is to review the technology Design and Process Failure Mode and Effect Analyses (FMEA) available from the technology developer. Most issues that can occur during technology integration are usually identified in the technology FMEA.

Before integrating a technology into a system, it is important to understand how sensitive a technology is in delivering its performance due to various causes of variation. The goal is to reduce technology performance variation which is the key to improving system reliability during the initial technology integration investigation. The standard tool used in establishing the performance robustness of a technology is the P-Diagram [11] (Figure 5). It allows one to understand the overall system behavior; identify functions, requirements and potential failure modes. The P-Diagram is required to achieve IRL2 criteria as stated in the IRL Table in the Reference section. The definition of IRL2 is as follow:

“There is some level of specificity to characterize the relationship between the technology and its interactions (i.e., ability to influence) with other systems through their interfaces. “

In a P-Diagram, the variables associated with a technology are the noise, control, signal (input) and response (output) factors. The noise factors are piece to piece variation, customer usage and duty cycle, degradation over time, environment and interaction with other systems. The control factors are the factors that can be controlled by the designer such as the type of material and mechanisms used to achieve the desired output. A technology will take an input signal and produce an output response. If the response is undesirable where it deviates from the target performance, the response is specified as an error state. If the desired response is achieved, the technology has achieved its “ideal function”.

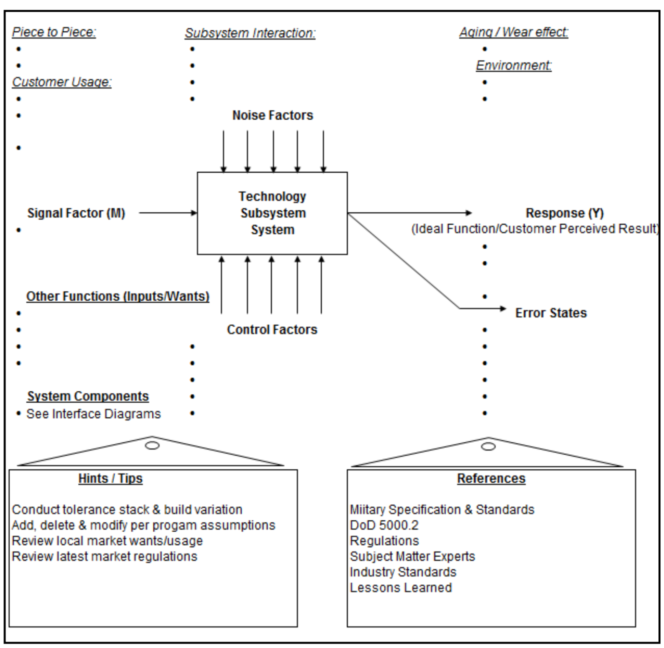

Figure 5 Technology P-Diagram

The goal of the robustness design is to minimize the performance response variation by choosing the proper and low cost control factors. A high signal-to-noise ratio indicates a good quality system. If the control factors are independent of each other in influencing the system response, the control factors are said to have orthogonal characteristics. Note that other standard tools such as Design of Experiment (DOE) can be used in conjunction with the P-Diagram to determine the performance robustness of a technology within a system.

Qualitative risks can be established from using various risk checklists developed from lessons learned from past program execution. A good checklist for qualitative risks is the US Air Force Risk Identification: Integration and Ilities (2009) also referred to as RI3. In the RI3 report [8], the risks are broken down into nine primary categories. The following qualitative risks are related to integrability category:

1. Are Interface Control Documents (ICDs) for the component/subsystem and levels below on track to be completed and adequately resourced (or already completed)?
2. Do existing ICDs clearly define information (hardware and software) that is to be passed between integrating units, and do they reference MIL STDs and/or industry standards when appropriate?
3. Do the ICDs at various levels of integration have traceability back to the requirements?
4. Where there are interdependencies/interactions between internal and external elements (e.g. EMI, contamination, vibration, dissimilar metals, etc.), have those inter-dependencies / interactions been adequately addressed by the ICD?
5. Where there are interactions between units (internal or external to both systems and components) coming from different suppliers, have steps been taken to identify and mitigate any potential proprietary or trust issues?
6. Have appropriate size, weight, power (SWAP), and thermal margins, integration into existing data buses, information sharing, mission systems been established and are they being maintained as appropriate for the stage of the program?
7. SWAP and thermal considerations) been properly vetted through all organizations responsible for impacted components and subsystems (including customer)?
8. Are all contractors & subcontractors part of the integration team?
9. Have modeling and simulation of the system, including its subsystems and its interaction with other system elements been performed with sufficient detail to establish test objectives and exit criteria (including reliability, maintainability)?

10. Is the system level modeling sufficiently detailed to demonstrate interactions with, external systems with which it is required to operate? What are the cumulative effects /impact on the overall platform as a result of these integration issues (overweight, short on power & mobility, at the capacity of power generation, design limits)?
11. Have all modeling and simulation tools been appropriately validated / certified?
12. Have key subsystems at whatever level of readiness (breadboard, brassboard, prototype) been demonstrated together in an integrated test environment?
13. Are integration tests being done early enough to influence/inform higher levels of integration?
14. Are there any issues involving certification or regulation in the proposal? Will there be any issues for the warfighter to use the subsystem in the field?

The technical risk identification process during the technology development phase is represented in the following flowchart (Figure 6).

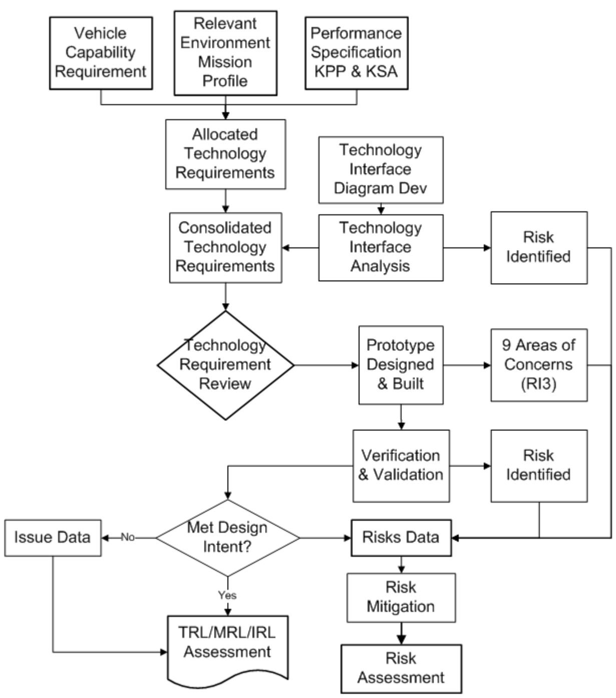

Figure 6 TD Phase Technology Risk Identification Process

CONCLUSION

To satisfy TRL6 criteria, the technology shall be tested in a representative prototype in a relevant environment. Similarly, to satisfy IRL6 criteria, all interfaces and constraints related to the technology or subsystem shall be identified, understood and characterized.

The key to integrating a technology successfully is to collaborate with those who are responsible for the interacting subsystems and jointly agreed on the interface requirements, test methods and acceptance criteria. The best practice in capturing the interface requirements is to use the interface/boundary diagram (Figure 2).

The interface/boundary diagram of a technology shall include the technology itself, any components, subsystems or systems that interact with it and the constraints that are imposed on it. It is normally created by a team of engineers responsible for the interacting subsystems from various functional organizations (design, manufacturing, test, safety, service, etc).

The nature of the interfaces shall be defined in detail (requirement metrics, required of or required by) with the understanding that these interfaces will eventually be developed into interface requirements that need to be demonstrated under real world environment.

The P-Diagram is a tool used to characterize a system so that the system performance robustness can be analyzed. The purpose of managing the technology to system interfaces is to make the technology insensitive to variations caused by noise generated by interacting systems.

A complete integration risk assessment shall include both the quantitative and qualitative risk assessment.

Quantitative risks are risks that the system with the integrated technology may fall short of meeting any engineering requirements such as system reliability or unacceptable performance variability. Qualitative risks are usually expressed in various checklists that are developed from systems engineering best practices or lessons learned. These risks can be grouped into 9 main categories: design, scalability/complexity, integrability, testability, software, reliability, maintainability, human factors and people/organization/skills.

The IRL is an indicator for showing how much a technology has been integrated into a system by looking at the characterization of technology interface with other interacting systems, and the functional demonstration of an integrated system to meet its performance target.

In this paper, a new set of IRL definitions have been proposed to complement the TRL definitions by providing a focus on technology integration. TRL measures technology maturity by the level of component/subsystem/system testing achieved. IRL measures technology maturity by the level of integration achieved between the technology and the interacting systems. TRL and IRL are related in a sense that a technology has to be integrated into a system before the system can deliver its system functions. Examples of Interface/Boundary Diagram and P-Diagram are included to explain the standard technology integration tools used in assessing the IRL. Finally, a flowchart is also included to further show the actual steps used in identifying both quantitative and qualitative risks in recent TRA of US Army vehicle programs. Both TRL and IRL are required to evaluate the overall technology readiness. TRL is used to assess if a technology/subsystem meets the performance requirements through testing. IRL is used to assess if a technology/subsystem is properly interfaced with other interacting systems functionally and physically under environmental and regulatory constraints.

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Integration Readiness Levels (IRL)

IRL	Definition	Description	Questions To Consider
1	Interfaces have been identified with sufficient detail to allow characterization of the relationship between the technology and its interacting systems and constraints.	Interfaces between technology and its interacting systems and constraints have been identified. Capabilities exist to provide a solution for a need, but little consideration has been given to potential applications & integration schemes.	1. Have the top-level functional architecture & interface points been defined? 2. Have the technology and its interacting systems interfaces and constraints been identified and documented? 3. Have the technology interface media been selected?
2	There is some level of specificity to characterize the relationship between the technology and its interactions (i.e., ability to influence) with other systems through their interfaces.	Applications defined. Broad performance goals identified. Proposed configuration concepts developed and modeled enough for "Proof of Concept" for the integration technology. Some generalized integration Configuration Item (CI) interface schemes have been proposed.	1. Are the inputs/outputs for the technology known, characterized & documented? 2. Have the technology/system **P-Diagram** (signal/noise, reliability) been drafted to understand how the technology works within a system or environment?
3	Integration features for integrating technology elements have been modeled.	Top level performance requirements defined. Trade-offs in design options assessed based on models. Product lifecycle and technical requirements evaluated. Integration features for integrating technology elements have been modeled. There is compatibility (i.e., common language) between the embedded technology and its environment to orderly & efficiently integrate & interact.	1. Have the technology/system P-Diagram been finalized to understand how the technology works within a system model or environment? 2. Has high-level **technology/system interface diagram** been established with interacting systems? 3. Has **interface analysis** been started to demonstrate compatibility between technology and interacting systems? 4. Are the interface requirements defined at the concept level?
4	There is sufficient detail in the quality & assurance of integrating the technology into a system model.	Technology has proposed interfaces established for a targeted platform. Plan established for technology insertion and System Integration Lab test. Initial potential Key Performance Parameters (KPPs) identified for preferred systems concept (PSC). Integration CI characteristics & measures to support required capabilities identified. Form, fit, & function constraints identified & manufacturing capabilities identified for integration CIs. Limited functionality for integration elements has been demonstrated via simulation, or a preliminary integration scheme has been implemented to permit collection of integration technology performance data in a laboratory.	1. Are overall system requirements for end users' application known / baselined? 2. Have interface analysis been completed for PSC? 3. Has the communication between technology and its interacting systems been demonstrated reliably and accurately? 4. Has a rigorous requirements inspection process been implemented? 5. Have the system integration plan been established?
5	Major technology functions demonstrated within component prototypes, engineering models or in laboratories.	Lower level performance requirements sufficient to proceed to preliminary design. All enabling/critical technologies & components identified for the product lifecycle. Evaluation of design Key Characteristics (KC) initiated. Product data required for prototype component manufacturing released. Major functions of the integrating technology have been demonstrated with prototypes, engineering models or in laboratories. There is sufficient Control between technology and the targeted platform necessary to establish, manage, & terminate the integration.	1. Has an Interface Control Plan been implemented (i.e. Interface Control Document created, Interface Control Working Group formed, etc.)? 2. Have interface requirements and acceptance criteria been well established (i.e. source, data formats, structure, content, method of support, etc.) and concurred by interacting systems?
6	Integration element baseline established.	Integration element baseline established; platform interfaces have all been identified and agreed to. All enabling/critical technologies/components for the integration CIs have been demonstrated. Preliminary design KCs defined. Notional interface proposals with constraints have been established (mechanical, all required vehicle modifications to accept technologies to be integrated, electrical/cabling, wireless protocol, security, human interface etc.). The integrating technologies can Accept, Translate, and Structure Information for its intended application.	1. Have individual systems been tested to verify that the system components work together? 2. Have integrated system demonstrations been successfully completed? 3. Have all interface requirements been met by tests or analysis (systems work together) in relevant environment? 4. Have all interface requirement non-compliance been reconciled and documented?
7	Technology integration has been verified and validated with sufficient detail to be actionable.	Product requirements and features are well enough defined to support critical design review, even though design changes may be significant. All product data essential for component manufacturing has been released. Potential KC risk issues have been identified and mitigation plan is in place. Full prototype integration CIs have been successfully integrated and shown to have functional requirement compliance in SILs. Demonstrated in a representative alternative system.	1. Has end-to-end functionality of the systems integration been successfully demonstrated? 2. Has each system interface been tested individually under stressed & anomalous conditions? 3. Has the fully integrated prototype been demonstrated in actual or simulated operational environments?
8	Functionality of integration technology has been demonstrated in prototype modified vehicles	Detailed design of product features and interfaces is complete. All product data essential for system manufacturing has been released. Design changes do not significantly impact Low Rate Initial Production (LRIP). KCs are attainable based upon pilot line demonstrations. Component and element specifications have been established and been agreed to by CI component and platform integrating manufacturers. Functionality of integration items has been demonstrated in prototype modified vehicles.	1. Are all integrated systems able to meet overall system requirements in an operational environment? 2. Have system interfaces been qualified and functioning correctly in an operational environment? 3. Has integration testing been closed out with test results, anomalies, deficiencies and corrective actions documented?

9	Actual integration completed and Mission Qualified through test and demonstration in the system environment.	Product design features and configuration are stable. System design has been validated through operational testing of LRIP items. Physical Configuration Audit (PCA) or equivalent complete as necessary. Design freeze is in place. All changes require formal Engineering Change Proposal (ECP) approval process. All KCs are controlled in LRIP to threshold quality levels. All component, element, assembly and subsystem specifications have been demonstrated to be satisfied in a repeatable fashion in the mass production facilities using specified materials, process, machinery, equipment and tooling.	1. Has a fully integrated system demonstrated operational effectiveness and suitability in its intended or a representative operational environment? 2. Have interface failures/failure rates been fully characterized and consistent with user requirements?

Technology Readiness Levels (TRL) for reference

TRL	Definition	Description	Questions To Consider
1	Basic principles observed & reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research & development (R&D). Examples might include paper studies of a technology's basic properties.	1. Have the physical laws & assumptions used in this technology been defined? 2. Are paper studies available to confirm basic principles? 3. Has a research hypothesis been formulated?
2	Technology concept &/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, & there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	1. Have the basic elements of the technology been identified? 2. Are paper studies available that indicate the application is feasible? 3. Are the experiments that need to be performed to research the technology known?
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	1. Have predictions of technology capability been validated by analytical studies? 2. Are paper studies available that indicate the system components ought to work together? 3. Has scientific feasibility been fully demonstrated?
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	1. Have laboratory experiments with available components of the system show that they can work together? 2. Has low fidelity system integration and engineering been completed in a lab environment? 3. Has a functional work breakdown structure been developed?
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	1. Are the system interface requirements known? 2. Has high fidelity lab integration of the system been completed and the system ready for test in realistic/simulated environments? 3. Is the physical work breakdown structure available?
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	1. Has the engineering feasibility been fully demonstrated? a. System requirements finalized (reliability, technical, etc)? b. Operating environment defined? 2. Has a representative model/prototype been tested in a high-fidelity lab or simulated operational environment? a. Relevant environment defined? b. Tested at relevant environment? c. What is the margin of safety, test to failure, sensitivity (robustness)? 3. Has M&S been used to simulate system performance in an operational environment? a. M&S and test correlation?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an air-craft, in a vehicle, or in space).	1. Has the system been tested in an operational environment, but not the eventual platform? 2. Has the system prototype been successfully tested in a field environment? 3. Has M&S been used to simulate some unavailable elements of the system?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	1. Has the system been formed, fitted, and function designed for its intended platform? 2. Has all functionality been demonstrated in simulated operational environment? 3. Has the system been qualified through test and evaluation on the actual platform (DT&E completed)?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	1. Has the Operational Concept been implemented successfully? 2. Has the actual system been fully demonstrated? 3. Has the system been installed and deployed in its intended platform?

BIOGRAPHY

JEROME TZAU is a systems engineer with the US Army within the Tank Automotive Research Development Engineering Center Systems Engineering and Integration Group for the last five years. His experience includes 14 years of applying systems engineering as a technical specialist in Body Engineering for Ford Motor Company and 14 years of jet engine design for General Electric. His interest is in the development and application of systems engineering processes with a focus in technical risk assessment, technology maturity assessment, requirement management and system engineering plan development in the DoD Science and Technology and Acquisition programs. He holds a MS in Mechanical Engineering from the University of Illinois and a BS in Mechanical Engineering from the University of Rochester.