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From TRL to SRL: The Concept of Systems Readiness Levels

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Abstract

Since the 1980's the National Aeronautics and Space Administration (NASA) has used technology readiness level (TRL) as a means to assess the maturity of a particular technology and a scale to compare technologies. In 1999, the Department of Defense (DoD) embraced a similar TRL concept in their programs. The TRL scale is a measure of maturity of an individual technology, with a view towards operational use in a system context. A more comprehensive set of concerns become relevant when this assessment is abstracted from an individual technology to a system context, which may involve interplay between multiple technologies. We are proposing the concept of a System Readiness Level (SRL) that will incorporate the current TRL scale, and introduce the concept of an integration readiness level (IRL) to dynamically calculate a SRL index. We present the foundations of the SRL and our methodology for developing, validating, and verifying its operational use.

Introduction

In the 1980's the National Aeronautics and Space Administration (NASA) instituted a seven level Technology Readiness Level (TRL) metric to assess the risk associated with technology development. By the 1990's this metric had evolved into the nine levels that exist today and has become widely used across NASA as a systematic metric/measurement system to assess the maturity of a particular technology and to allow consistent comparison of maturity between different types of technologies. Given the pragmatic utility of this concept, in 1999, the Department of Defense (DoD) embraced a similar TRL concept. While the use of TRL is similar in both NASA and the DoD, there is a slight variation in the interpretation of TRL in these two organizations. For example, NASA specifies that technologies should mature until a TRL 6 before a mission can assume responsibility for the technology (Shishko, et al. 2003) and DoD states that a technology should reach the equivalent of TRL 7 before they are included in a weapons system program (GAO July 30, 1999).

These small differences notwithstanding, along with the successful use of the TRL metric to evaluate the maturity of technology development, it has been stated that TRL:

1. does not provide a complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system (Dowling and Pardoe 2005, Mankins 2002, Meystel, et al. 2003, Smith 2005, Valerdi and Kohl 2004),
2. includes no guidance into the uncertainty that may be expected in moving through the maturation of TRL (Cundiff 2003, Dowling and Pardoe 2005, Mankins 2002, Moorehouse 2001, Shishkio, et al. 2003, Smith 2005), and
3. assimilates no comparative analysis technique for alternative TRLs (Cundiff 2003, Dowling and Pardoe 2005, Mankins 2002, Smith 2005, Valerdi and Kohl 2004).

Based on these fundamental conjectures, a more comprehensive set of concerns becomes relevant when TRL is abstracted from the level of an individual technology to a system context which may involve interplay between multiple technologies. Considerations relating to integration, interoperability, and sustainment become equally important from a systems perspective in an operational environment.

In order to address the concerns relevant at the operational system level, the concept of a System Readiness Levels (SRL) is proposed herein. It incorporates the current concept of the TRL scale, while also including the notion of Integration Readiness Levels (IRL) to dynamically calculate a SRL index. Considerations underpinning the foundations of the proposed SRL concept are discussed in this technical paper, together with the methodology for developing, validating, and verifying its relevance and utility for an operational system. We will conclude with a discussion of the future objectives of correlating this SRL model to appropriate systems engineering management principles.

Moving Beyond TRL

The development of TRL beyond its current nine levels (see Table 1) and into a more dynamic metric for assessing technology has been a part of numerous NASA and DoD focused research efforts. Much of the early work in this area was in defining the risks and costs associated with various TRL levels. These studies helped to expand the definition of respective TRLs, but still did not address the issues related to the integration of technologies or the progression through the TRL scale.

The first study that attempted to expand TRL to consider an index and methodology for maturity difficulty through the TRL scale was done by Mankins (2002). He proposed an integrated technology index (ITI) that was a discipline-neutral, quantitative measure of the relative technological challenge inherent in various candidate/competing

Table 1: Technology Readiness Levels

TRL	Definition
9	Actual System Proven Through Successful Mission Operations
8	Actual System Completed and Qualified Through Test and Demonstration
7	System Prototype Demonstration in Relevant Environment
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment
5	Component and/or Breadboard Validation in Relevant Environment
4	Component and/or Breadboard Validation in Laboratory Environment
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
2	Technology Concept and/or Application Formulated
1	Basic Principals Observed and Reported

advanced systems concepts. The methodology, Integrated Technology Analysis Methodology (ITAM), then included a consistent hierarchy of subsystems and technologies across competing systems; identification of a TRL, Delta-TRL, R&D Degree of Difficulty; and a Technology Need Value; and synthesis of technology metrics across technologies and subsystems to determine an ITI. This then allows a comparative ranking of systems based on their ITI. While this study brought to the forefront the difficulty of moving through the TRL index and allowed for comparing individual technologies, it did not adequately address the integration aspects of system development.

Meystel et al. (2003) brought attention to the issue of integration in their white paper on performance measures for intelligent systems by presenting detailed definitions of the nine TRLs and discussing the uncertainty and complexity of TRL integration, but did not present an integration solution. Shenhar et al. (2005) showed how TRL could be correlated to project risk and technological uncertainty for developing a project management framework, but only presented a static solution. Likewise, Valerdi and Kohl (2004) gave further attention to the impact that the maturity of a technology can have on system success when adopting the technology into a system. In response to some of these risks identified with technology maturity and the DoDs desire to take some of the ambiguity out of TRL, a research team with the Air Force Research Laboratory (AFRL) developed a dynamic TRL calculator (Nolte, et al. 2004). Using a Microsoft Excel spreadsheet application, a user can answer a standard set of questions about the developmental state of a technology and receive a graphical display not only of the technologies TRL, but how the technology rates above and below the scored TRL. It provides the user with a repeatable system for measuring a technology's maturity, snap shot of program maturity at a given time, and historical picture of what has been done thus far.

Aside from Mankin's earlier work, there have been three other independent efforts to expand or enhance the TRL metric. First, the DoD introduced the concept of manufacturing readiness levels (MRL) to expand TRL to incorporate producibility concerns related to risks associated with time and manufacturing. MRLs are a metric that assesses the system engineering/design process and maturity of a technology's associated manufacturing processes to enable rapid, affordable transition to acquisition programs. The MRL index is used early in the development phase for acquisition program managers to comply with the DoD 5000.1 mandates (Cundiff 2003). Second has been the work of Smith (2005) at Carnegie Mellon Software Engineering Institute who expanded TRL to include additional readiness attributes of requirements satisfaction, environmental fidelity, criticality, product availability, and product maturity to define a evaluation framework of similar technologies. The third and most extensive developments have been by the United Kingdom's Ministry of Defence (MOD). Based on concerns for successful insertion of technology into a system, they have developed a Technology Insertion Metric that includes TRL, a Sytems [Integration] Readiness Level, and Integration Maturity Level (Dowling and Pardoe 2005). They have then correlated systems engineering practices for each index based on phases in the systems engineering process and MOD Policy.

Why a Systems Readiness Level

While the efforts previously described have greatly expanded and enhanced our understanding of TRL, it is our premise that TRL is not an end state to determining a system's readiness based on:

- TRL is only a measure of an individual technology and not systems readiness;

- There is no method for integrating TRLs; and
- There is no proven, tested, systematic index of systems readiness

In theory, technology and systems development follow similar evolution (or maturation) paths, and technology is inserted into a system based on its maturity, and ability to integrate into the intended system. Some have described TRL as not only a measure of a technology maturity, but also a measure of its integration readiness, but we contend that two TRL 9s, technology mature, can be a different levels of integration maturity.

Figure 1 shows how a phased system development path and TRL evolution can be compared and their similarity. One of the fundamental premises of our research is that while theoretically technology and system development may be parallel paths, they are not integrated paths. We will give an example of this premise using a well recognized system failure, NASA's Mars Climate Orbiter (MCO). MCO was planned to circle Mars and collect the planet's weather data as well as act as a relay station, assisting in data transmission to and from Mars Polar Lander, which was designed to land on Mars' South Pole. Soon after MCO began its insertion maneuver, the orbiter's signal was lost and was never recovered again. A peer review committee confirmed the engineers' assessment that small forces of velocity change used in orbit insertion were lower than expected by a factor of 4.45. The Mishap Investigation Board later idenified the root cause of MCO's loss as a failure to use metric units in the coding of a ground software file. While the technology or core design concepts were considered proven, the linkages or architecture of the design were new in relation to the navigation system. With minor changes in the component system (e.g. navigation system), it created new interactions and new linkages with other components in an established product. We describe this integration error with MCO further when we present an integration readiness level index.

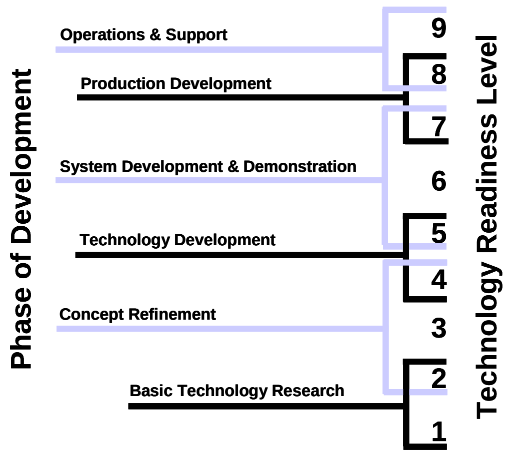

Figure 1: System Phases of Development and TRL on Parallel Paths

We contend that a true system readiness level should consider technology readiness as well as the achieved maturity and readiness involved with integrating it with the intended and operational system. Ruben and Kim (1975) proposed four basic assumptions that underlie all systems and provide a basis for unification:

1. The sum is greater than the parts and there are consequences for not understanding the dynamics of each part;
2. There is multilateral causality among subsystems, systems, and the environments they function in;
3. One set of initial conditions can give rise to different final states; and
4. There is concern with the flow of information between subsystems (components)

We considered these four basic assumptions in the development of the system readiness level index we will present in this paper. While we have not fully explored the third assumption, we believe that by introducing an integration index and understanding the functions that govern the relationship between the TRL and their integration to determine a system readiness level index, we are considering assumptions one, two, and four.

System Readiness Level (SRL) Index

The System Readiness Level (SRL) index is an index of maturity applied at the system-level concept with the objective of correlating this indexing to appropriate systems engineering management principals. We contend that the SRL of a given system is a function of individual TRLs and the maturities of the links between them, which will be defined based on a scale of integration readiness levels (IRLs). To understand this SRL dynamic we first endeavored to understand the relationship between TRL and IRL and how they are used to transform qualitative descriptions into quantitative maturity levels. In the following sections we will describe the theory and development of the TRL, IRL, and SRL indices, the methodology we used to understand the dynamic relationships, and how we will continue to validate and mature the SRL model.

Technology Readiness Level (TRL)

The key observation with regard to the TRL scale is that it only evaluates the maturity of an individual technology. As can be observed by the various descriptions depicted in Table 1, TRL takes a given technology from basic principals to concept evaluation through to 'breadboard' validation, then to prototype demonstration, and finally to completion and successful mission operations. While these characterizations are very useful in technology development they say nothing about how this technology integrates within a complete system. It is our contention that most complex systems fail at the integration points.

Integration Readiness Level (IRL)

We define IRL as a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (TRLs). We propose using IRL to describe the integration maturity of a developing technology with another technology, developing or mature. The addition of IRLs not only provides a check to where the technology is on an integration readiness scale, but also a direction for improving integration with other technologies. As TRL has been used to assess the risk associated with developing technologies, IRL is designed to assess the risk of integration. Valerdi and Kohl (2004) stated TRL does not accurately capture the risk involved in the adopting of a technology, and Smith (2005) showed that technologies can have an architectural inequality related to integration. As system's complexity increases (i.e. a large interconnected network) there must be a reliable method and ontology for integration that allows TRLs to collectively combine for develop these complex systems.

Table 2: Summary of the OSI Layers

Layer	Name	Description
7	Application	Support for applications
6	Presentation	Protocol conversion, data translation
5	Session	Establishes, manages, and terminates sessions
4	Transport	Ensures error-free packets
3	Network	Provides routing decisions
2	Data Link	Provides for the flow of data
1	Physical	Signals and media

In order to measure the integration we worked to develop an index that could indicate how integration occurs. This index must consider not only physical properties of integration, such as interfaces or standards, but also interaction, compatibility, reliability, quality, performance and consistent ontology when two pieces are being integrated. To create an index of integration that conforms to these requirements there needs to be some starting point to provide the correct structure on which to build. We selected the seven layer Open Systems Interconnect (OSI) model used in computer networking to structure data being transmitted on the network, and allow for integration of many different technologies onto the same network. Table 2 describes the structure of the OSI model (Beasley 2004).

Using this very specific model to build a generic integration index required first examining what each layer really meant in the context of networking and then extrapolating that to general integration terms. We took layers 1 - 3 as interface, interaction, and compatibility, respectively, Layer 4 as a data integrity check, Layer 5 as an integration control, Layer 6 as the interpretation and translation of data, and Layer 7 as the verified and validated integration of two technologies. With these new layer descriptions, integration readiness levels were then developed to describe the maturity of the integration between any two technologies. Table 3 is a listing of the IRL indices and their associated definitions. As an example, we go back to the MCO integration error. MCO failed due to an inability to receive a measurement in metric and then executing a formula based on English units. This error can be represented as more than a failure in compatibility or IRL 3 (i.e. a number was sent, and received as a number, just with no units). Had there been the ability to translate the data into another measurement system, and the understanding between technologies that the transmitted number was in a specific measurement system, this could have been a successful integration. Therefore, if there existed a pre-defined protocol for transmitting measurements it would include not just the magnitude but also the units, so when it is received, it can be translated into the local units of the technology that is receiving it, this is an IRL 6.

Table 3: Integration Readiness Levels

IRL	Definition
7	The integration of technologies has been ***verified and validated*** with sufficient detail to be actionable.
6	The integrating technologies can ***accept, translate, and structure information*** for its intended application.
5	There is sufficient ***control*** between technologies necessary to establish, manage, and terminate the integration.
4	There is sufficient detail in the ***quality and assurance*** of the integration between technologies.
3	There is ***compatibility*** (i.e. common language) between technologies to orderly and efficiently integrate and interact.
2	There is some level of specificity to characterize the ***interaction*** (i.e. ability to influence) between technologies through their interface.
1	An ***interface*** (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterization of the relationship.

System Readiness Level (SRL)

The SRL index is designed to be a function of the individual TRLs in a system and their subsequent integration points with other technologies, IRL. The resulting function of this interaction is then correlated to a five level SRL index. This SRL index was defined by the current state of development of a system in relation to the DoD's Phases of Development for the Life Cycle Management Framework as described in Table 4 (DoD 2005). We do not promote the DoD phases as the only system phases of development, however, these are consistent with other life cycle models and is used for illustration purposes in the context of this research.

Table 2: System Readiness Levels

SRL	Name	Definition
5	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	*Production & Development*	Achieve operational capability that satisfies mission needs.
3	*System Development & Demonstration*	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	*Technology Development*	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	*Concept Refinement*	Refine initial concept. Develop system/technology development strategy

Verification and Validation of the SRL

The first step in our development of a SRL was to understand the dynamic relationship that may occur between TRL and IRL in their component-level impact on system readiness. To accomplish this we narrowed the focus of our SRL model to two technologies (TRL) and their integration (IRL) into a simple system. By completely understanding the TRL-IRL-TRL variations that combine to create the SRL, we can use network modeling to apply this concept to large, interconnected systems and determine how component-level maturity and integration affects system-level maturity. The TRL-IRL-TRL variations can be enormous due to the fact that there are 9 TRLs and 7 IRLs which allows for up to 567 systems. Once all the systems that are the same forward and backward and systems that exceed an IRL of 1 with a TRL that is less than 3 are eliminated, the final total of valid systems is 171. The reason for eliminating any system with an IRL ≥ 1, and with a TRL ≤ 3 is that a technology only becomes a tangible breadboard design at TRL of 4, so integration is too immature with another technology until this point. Since 171 systems is still a large, yet manageable, amount of systems to classify into SRLs, we took a sample set of 26 systems that represented the potential dynamics that may indicate fluctuations in the SRL and the bounds around any SRL. Using these 26 systems, we took a top-down/bottom-up approach to determine the dynamic interactions between TRL and IRL. We created an online survey of the 26 systems which we would present to a subject with a simple TRL-IRL-TRL system and asks them to classify it in terms of SRL. They were also asked to provide comments on their reasoning for scoring a particular SRL.

Survey and SME Sampling

The survey was administered to 30 subjects determined to be subject matter experts (SME) in the field of system engineering and were selected from NASA, DoD, and private industry. They were presented with a simple system of a cell phone and wireless headset system, in which the cell phone and headset maturity were described by TRLs and their integration by an IRL. The 26 system variations that were presented in the survey all had the property that $TRL_{cell} = TRL_{headset}$. The logic was that while TRL variations are important, as stated earlier, we are specifically interested in the TRL-IRL influence at this stage of development.

Survey Results

We received a 33 percent response rate with the survey. Using the data, we were able to begin to understand the bounding of the systems that have the highest probability of being a specific SRL. We developed a scale based upon this data that would fit a specific system to the SRL in which it was most commonly associated. The assumptions are that a 1-1-1 is a SRL 1, and a 9-7-9 is a SRL 5, both with 100% certainty. Using these bounds we developed the scale represented in Figure 2, which represents how we will begin to define the indices to determine a SRL and the bounds around any SRL. Since we had a small sample size, we did not attempt to extrapolate a probability function. However, once more data is gathered, we plan to use a multinomial distribution to characterize the probability of being at a certain SRL as a random variable whose function is defined by TRL-IRL-TRL.

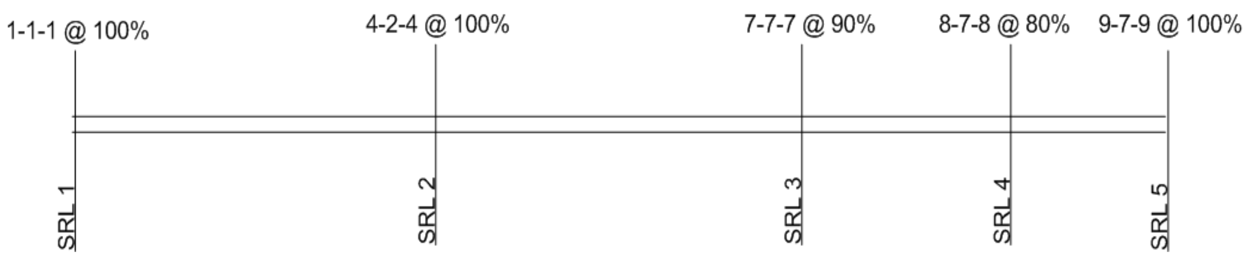

Figure 2: SRL Rank Distribution (not to scale)

Future Direction

We plan to continue administering the survey to strengthen the analysis and being the developments of the multinomial distribution with the end goal of developing the SRL index and model into a contingency framework for systems engineering. Classical structural contingency theory suggests that organizational effectiveness is dependent upon the organization's ability to adjust or adapt to the environment, and that there is a need for congruency between the environment and structure (Drazin and van de Ven 1985, Lawrence and Lorsch 1967, Pennings 1992). We plan to use contingency theory to analyze the extent of fit between system characteristics to define a preferred approach or style to systems engineering based on a SRL index. TRL and IRL are only the beginning of building a SRL. With the addition of a maturity difficulty, as depicted in Figure 3, we will have to consider other factors presented by Smith (2005), Mankins (2002), and others, as well as factors related to reliability, supportability, and maintainability. We still have many questions to answer such as: what are the correct factors for determining a SRL; how do you move SRL from a number to a threshold limit; and what are the best practices for successfully managing the gap between TRL, IRL and progressing through the SRL scale? The SRL model presented here is to be a first step in a contingency model for systems engineering that is built on the fundamental theory of a system.

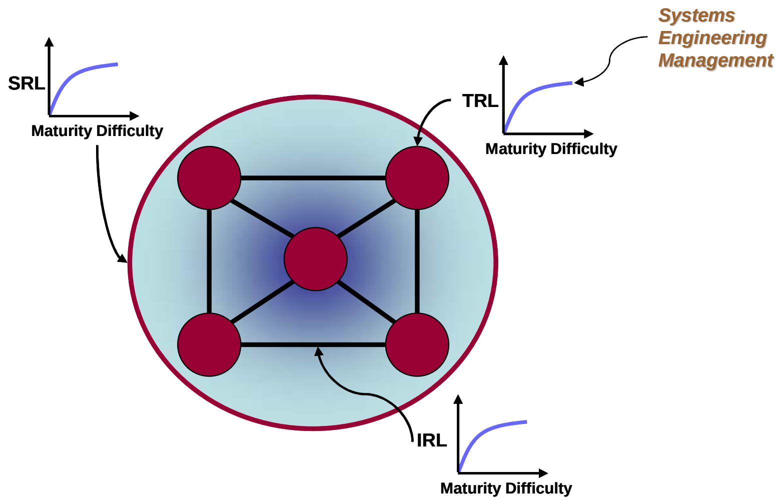

Figure 3: The Future SRL Model

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Biography

Brian Sauser, Research Assistant Professor, PhD., (2005), Stevens Institute of Technology and Director of Systems Engineering Management: came to Stevens from ASRC Aerospace at NASA Kennedy Space Center. He has worked in government, industry, and academia for more than 10 years as both a researcher/engineer and director of programs related to space science research. His research interests are in project management of complex systems.

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Jose E. Ramirez-Marquez, Assistant Professor, Ph.D., (2004), Rutgers University: came to Stevens from Rutgers University where he was involved in research focused on developing methods for optimizing system performance. He has also worked on modeling complex systems that have numerous performance levels.

Ryan Gove, Research Assistant, B.S., (2005), University of Delaware: came to Stevens in 2003 as an intern for WiNSeC (Wireless Network Security Center), where he worked on spectrum analysis and mapping of the 802.11 network, Public Safety Communications Interoperability, and Wireless Mesh Networking. Began his Master’s in Systems Engineering at Stevens in the Fall of 2005.