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10th Anniversary in Space Journalism (Space Ops - SOSTC): "Developing Propulsion Capability through Technological Milestones"

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Abstract
Over a twenty year post-Apollo period, over half the launches failed due to propulsion subsystems. The high levels of complexity associated with propulsion subsystems as well as the need to lower propulsion development costs indicated an issue with readiness management of propulsion technology portfolios in system development projects. Since risk analysis and response planning should be done during the initial phase subsystem development, greater assessment and evaluation of the technological readiness was considered. Systemic risks due to the complexity of component-component interdependencies initiating cascades of emergent, nondeterministic behaviors clustering toward a problem domain described more of a problem with subsystem complexity independent of subsystem technology readiness maturity or lack thereof. An unpredictable operative subsystem performance suggested a case study approach to investigate not only the technical artifact interactions at the component level of system hierarchy but the context in which the system is observed operative. System operations indicate a performance metric as the outcome of system usage. And, system usage suggests sequential tasks enacted on system circuitry of switches for a multistate environment of system operations. HMIs alignment specific to hierarchical level system complexity shows a synchronous situational awareness that is either managed with skill-, rule-, or expert knowledge- based decision making, or a safety instrumented system of sensors, programmable logic solvers, and actuators. Several models of problem solving protocols including Rasmussen's SRK model manage performance of system operations. Alternatively, preventative models of problem solving aim for a more fractionated restorable functioning performance post-disruptive hazards. Resilience-based CIMs determine the effect of the disruption, rather than the restoration such that CIMs identify system weaknesses and inform selective prioritization of reliability improvement activities of an individual component on network resilience.
Keywords: technology readiness, human-machine interactions, subsystem complexity, component information measurements, system network resilience.

Dear readers,
In celebration of the 20th anniversary of the *Journal of Space Operations Communicator*, a quarterly Space Ops-SOSTC (AIAA) publication, I am reminded of my debut into Space Ops Organization ten years ago with "Developing Propulsion Capability through Technological Milestones" presentation at the SpaceOps 2014 - 13th International Conference on Space Operations, 4-9 May, 2014 (Pasadena CA). At the time I had served over four years as Secretary, Orange County Section, AIAA (American Institute of Aeronautics and Astronautics) and was a doctoral candidate working on "system complexity of post- Apollo rocket engines which would later culminate into a dissertation on problem solving combustion instability from an organizational perspective". Considering rocket engine failures due to immaturity of propulsion technology rather than an issue of problem-solving manifested from system operational complexity required my delving into archived transcripts of Marshall SFC propulsion engineers interviewed during the Apollo Program. And that inquiry was the result of responding to a doctoral qualifying examination question relating to critical realism. A little over two years later I became a member of SOSTC (Space Operations & Support Technical Committee).

Background
National Institute Rocket Propulsion Systems (NIRPS) assessment of over 40 industry studies and historical analysis of performance reliability and costs in rocket engine development indicated long-term industry downsizing since 1979 and a shortage of new solid and liquid propulsion programs threatening U. S. leadership in rocket and missile propulsion. Since FAR Part 15 required limited insight into contract costs, DoD had regularly awarded Boeing and Lockheed-Martin (later ULA) for Delta IV and Atlas V launch services, respectively. In 2009, EELV prices skyrocketed that the Tiger Team of Air Force, DoD, National Reconnaissance Office, and NASA officials agreed to develop a new acquisition strategy that included no "block-buy" contracts; discontinuance of waivers in required reports of pricing and cost data; open competitive bids for launch contracts; and, single launch contract awards. When partnered with few large aerospace companies on a *cost plus contract fee* basis, NASA defined what and how partners develop space capability [1]. Comparatively, when NASA initiatives developed space exploration projects with many providers, and private and public users, contracts were negotiated on a *fixed fee* basis. NASA's Commercial Crew Integrated Capability (CCiCap) Space Act Agreements called for industry partners to develop crew transportation capabilities and to perform tests to verify, validate and mature integrated designs. SpaceX, Blue Origin and Virgin Galactic injected competition and innovation. NASA claimed savings of US $20 to $30 billion with the new commercial space ecosystem lowering costs by and opening doors for smaller players to enter the New Space ecosystem. The latest estimates put the number of space companies at well over 10,000 globally [2].

Earlier privatized efforts in the space launch vehicle industry was riddled with test flight failures, project cancellations, and company bankruptcies or closures in spite of few successes. Launches of US-built space vehicle from1984 to 2004 were riddled with propulsion subsystem problems causing 52 percent of all launch failures. A Futron Corporation study summarized root causes of 25 launch failures out of 470 total orbital launches during the same time period [3]. Propulsion subsystems represented over half of the launch vehicle subsystem failures [4]. The high levels of complexity associated with propulsion subsystems often provided opportunities for failure. The case for lowering propulsion development costs indicated readiness management of technology portfolios in propulsion system development projects. More than half different propulsion technologies identified in NASA's roadmaps had not matured to TRL 6 [5].The advanced propulsion technologies had TRLs 1-3.

Introduction
Technological Readiness Maturation Levels (TRLs 1-9) assess maturity of system readiness in terms of proof of concept, validated functionality, and sustained reliability. System readiness informs user expectations and intentions of their own technology readiness (or, Technology Task Fitness). NASA has long used Technology Readiness Levels (TRL) approach. TRLs assess the maturity of a particular technology and to track technologies in development and their transitioning into production processes.

Technology Readiness Metrics

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

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.

In the case of in-space propulsion technologies, NASA developed a Space Technology Roadmap (TA-02) for use by the National Research Council which in turn provided NASA with future technology investment recommendations.

Technologies Addressed in Formulation Task

1.0 Chemical Propulsion

- 1.01 Monopropellants
- 1.02 Bipropellants
- 1.03 High-Energy Propellants
- 1.04 High-Energy Oxidizers
- 1.05 LOX/Methane Cryogenic
- 1.06 LOX/LH2 Cryogenic
- 1.07 Gelled and Metalized-Gelled Propellants
- 1.08 Solid Rocket Propulsion Systems
- 1.09 Hybrid Rockets
- 1.10 Cold Gas/Warm Gas Systems
- 1.11 Solid Micropropulsion
- 1.12 Solid Cold Gas/Warm Gas Micropropulsion Systems
- 1.13 Hydrazine or Hydrogen Peroxide Monopropellant Micropropulsion

2.0 Nonchemical Propulsion

- 2.01 Resistojets
- 2.02 Arcjets
- 2.03 Ion Thrusters
- 2.04 Hall Thrusters
- 2.05 Pulsed Inductive Thrusters
- 2.06 Magnetoplasmadynamic Thrusters
- 2.07 Variable Specific Impulse Magnetoplasma Rocket
- 2.08 Microresistojets
- 2.09 Teflon Microcavity Discharge
- 2.10 Micropulse Plasma
- 2.11 Miniature Ion/Hall

2.0 Nonchemical Propulsion (Continued)

- 2.12 MEMS Electrospray
- 2.13 Solar Sail Propulsion
- 2.14 Solar Thermal
- 2.15 Nuclear Thermal
- 2.16 Electrodynamic Tether
- 2.17 Momentum Exchange Tether

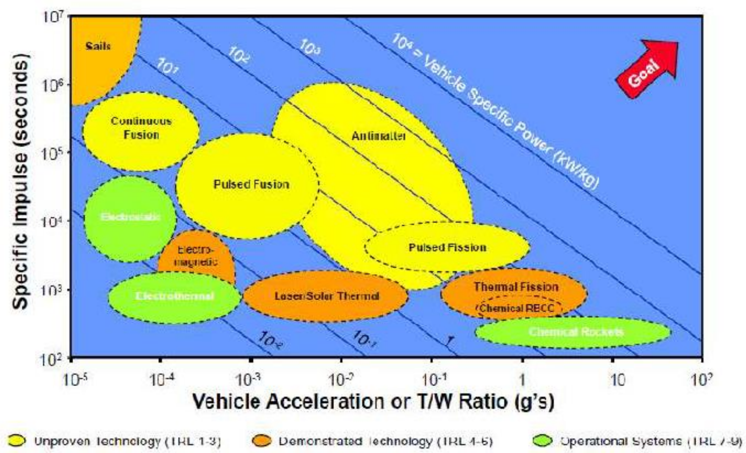
3.0 Advanced Propulsion Technologies

- 3.01 Beamed Energy Propulsion
- 3.02 Electric Sail Propulsion
- 3.03 Fusion Propulsion
- 3.04 Metallic Hydrogen
- 3.05 Atomic Boron/Carbon/Hydrogen
- 3.06 High Nitrogen Compounds (N4+, N5+)
- 3.07 Antimatter Propulsion
- 3.08 Gas Core Fission
- 3.09 Fission Fragment
- 3.10 External Pulsed Plasma Propulsion
- 3.11 Breakthrough Propulsion Physics

4.0 Supporting Technologies

- 4.01 Engine Health Monitoring and Safety
- 4.02 Propellant Storage, Transfer & Gauging
- 4.03 Materials & Manufacturing Technologies
- 4.04 Heat Rejection
- 4.05 Power

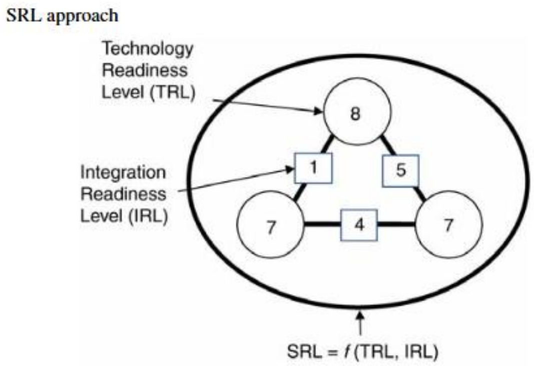
With a wide range of possible missions and candidate propulsion technologies, the technologies were developed to provide optimum solutions for a diverse set of missions and destinations [6]. Development of technologies resulted in technical solutions with improvements in thrust levels, Isp , power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, and of course, cost. These types of improvements yielded decreased transit times, increased payload mass, safer spacecraft, and decreased costs.



Defining "mission pull" a technology necessary to meet a planned NASA mission requirement and "technology push" as an alternate propulsion system, In-Space Propulsion Systems Technology Area (ISPSTA) prioritized challenges to urgency timeframes: near- (present to 2016), mid- (2017–2022), and far-term (2023–2028) time frames, representing the point at which TRL 6 is achieved. .

Rank	Description	
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems	N
2	Long-term in-space cryogenic propellant storage and transfer	M
3	High power (e.g. 50–300 kW) class Solar Electric Propulsion scalable to MW class Nuclear Electric Propulsion	M
4	Advanced in-space cryogenic engines and supporting components	M
5	Developing and demonstrating MEMS-fabricated electrospray thrusters	N
6	Demonstrating large (over 1000 m^2) solar sail equipped vehicle in space	N
7	Nuclear Thermal Propulsion (NTP) components and systems	F
8	Advanced space storable propellants	M
9	Long-life (>1 year) electrodynamic tether propulsion system in LEO	N
10	Advanced In-Space Propulsion Technologies (TRL <3) to enable a robust technology portfolio for future missions.	F

The broad objectives of testing vary depending upon whether the test article is at low-, mid-, or high- technology readiness level, and consequently the test campaign may be quite different in terms of approach and timeline. For low-TRL work, with proof-of-concept hardware, the emphasis is on expeditious turnaround of varying hardware configurations with sufficient test results to warrant focused follow-on testing. For mid-TRL work, the emphasis shifts towards a mature prototype design. For high-TRL propulsion devices, either engine components or engine systems, the highest level of rigor is applied to both the facility and test article hardware [7]. Key propulsion parameters for engine chamber pressure, area ratio, and oxidizer/fuel ratio, are optimized and plotted to show impacts to engine mass and overall vehicle mass [8]. Among the factors that characterize technology risk for subsystem development is uncertainty that technologies constituting the subsystem's technology portfolio will reach maturity for subsystem integration, and that technical performance measures will be met [9]. Risk analysis and response planning should be done during the initial phase. Assessing development difficulty includes evaluating the technological readiness level gap (initial to TRL 6) and the research and development (R & D) degree of difficulty. Maturing the technology is a time as well cost consuming process.



TRLs fail to completely represent the difficulty of integrating the subject technology into an operational subsystem, and fails to assimilate a comparative analysis technique for alternative TRLs. TRLs related to a single technology within a subsystem context implements differently than when the interplay between multiple technologies of a single technology portfolio is introduced. System Readiness Levels (SRL) addresses the concerns of integration, interoperability, and sustainment of multiple technologies from a system's operational perspective. Different technologies mature at different rates. Therefore Integration Readiness Levels (IRL) intermediately function as TRL-IRL-TRL readiness unit to prepare for system's simultaneous implementation of multiple technologies. IRL measures the interfacing between compatible interactions for different technologies and a consistent comparison of their TRLs at integration points prior to subsystem incorporation. IRLs are used to describe the integration maturity of a developing technology with another technology that is developing or is already mature. Whereas TRL assess risk associated with developing technologies, IRLs assess risk related to their integration. With increased performance-driven system complexity, such IRL methodologies provide for TRLs to collectively combine for system complexity.

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

TRL related to a single technology within a subsystem context implements differently than when the interplay between multiple technologies of a single technology portfolio is introduced. System Readiness Levels (SRL) addresses the concerns of integration, interoperability, and sustainment of multiple technologies from a system's operational perspective. Different technologies mature at different rates. Therefore Integration Readiness Levels (IRL) intermediately function as a of TRL-IRL-TRL readiness to prepare for system's simultaneous implementation of multiple technologies. IRL measures the interfacing between compatible interactions for different technologies and a consistent comparison of their TRLs at integration points prior to subsystem incorporation. IRLs are used to describe the integration maturity of a developing technology with another technology that is developing or is already mature. Whereas TRL assess risk associated with developing technologies, IRLs assess risk related to their integration. With increased performance-driven system complexity, such IRL methodologies provide for TRLs to collectively combine for system complexity. Operational system readiness level considers the different dynamics of each assembled subsystem, hence the need for a Systems Readiness Level (SRL) for the following reasons: (1) there is multilateral causality among the subsystems' IRLs. The integration of technologies verify sufficient detail to be actionable. The integrating technologies accept, translate, and structure information for their intended applications. There is sufficient control between technologies necessary to establish, manage, and terminate the integration. There is sufficient detail in the quality and assurance of the integration between technologies. There is compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact. There is some level of specificity to characterize the interaction (i.e. ability to influence) between technologies through their interface. An interface between technologies identified with sufficient detail allows characterization of the relationship. (2) one set of initial conditions exhibit in different final states; and (3) performance uncertainty relates to information flow between component subsystems [10].

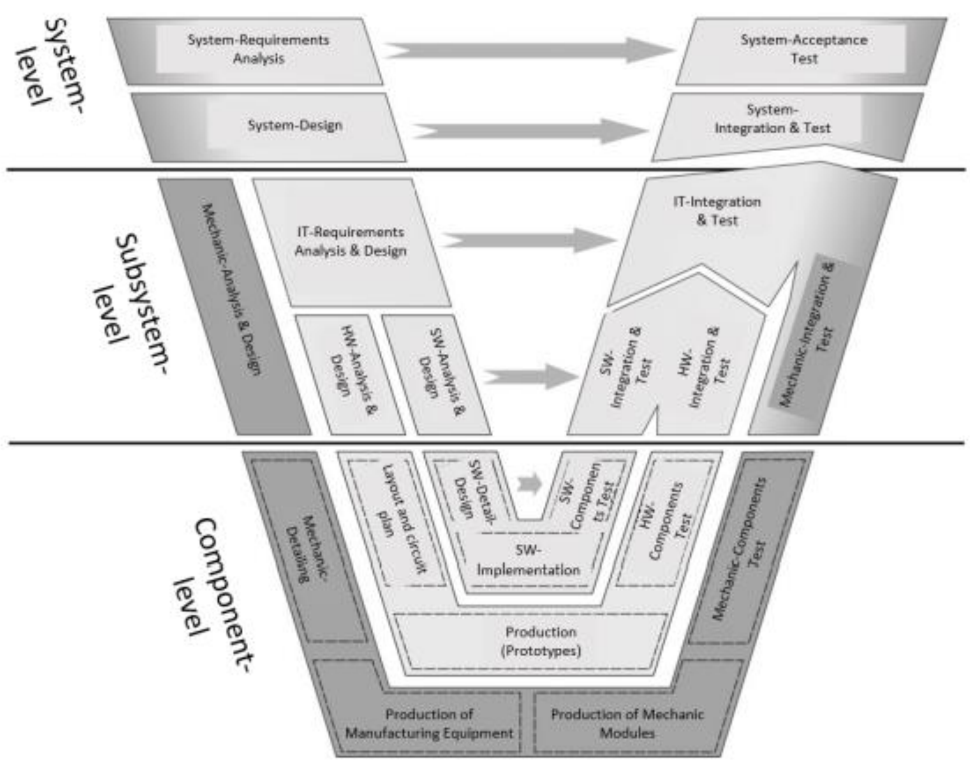
Discussion

The probability of project failure indicates technical l failure of performance, as well as programmatic failure of costs and schedule [11] all of which manifest from both observed and unobserved structures and inter-structural relations. Unobserved structures and inter-structural relations relate to subsystem complexity. Therefore, TRL 5-TRL 6 transition is important based on the focus of validation of technological components integrated with realistic supporting elements so that the technology can be tested in a simulation environment. The inability to adequately measure uncertainty when technology matures and integrates into the larger system [12] points to the need for exploring component level integration, interoperability, and sustainability. Effective integration studies at the component level may require greater rigor and different tools. [13] recommended an Integration Maturity Metric (IIM) to determine integration maturities of nested component configurations and a metric to examine different levels of sub-system architecture. The latter would require (1) access to a user interface integrating the components; (2) access to data of one component to access data of another component; and (3) access to the integrating components executing internal functionality [14]. More than one component would store the data but the overall data would be controlled centrally [15]. There is greater demand for data describing inter-operability of two or more components [16].

System complexity. Factors characterizing technology risk include uncertainty that subsystem technology portfolios will not reach maturity for subsystem integration and that technical performance measures will not be met [17]. The need for sensors to monitor engine behaviors provides both documentation and feedback for corrective re-design and re-engineering. Therefore, co-development of propulsion and sensor technologies indicates an additional need for compatible requirements engineering. According to [18]. TRL transition costs reduce significantly after median TRL4-TRL5 transition. However, costs may be understated for TRL5- TRL6 due to less component analysis where nondeterministic, nonlinear behaviors arise from component-component interactions. Technology-driven strategies develop radical innovation toward a functional performance limit, which eventually exposes hidden technical complexities [19]. Critical Realism Theory describes causality with regards to how processes are generated by structures and contextual conditions [20].The context of multiple interacting structures with potential to generate an event [21] include heuristic rules and practices as well as technological artifacts. Complex systems contain component parts which of themselves are technical artifacts. Their unknowing behaviors evolve over time and are neither parameter-controlled, predictable, linear, or deterministic [22]. Many researchers consider the case study, the best method to explore interaction of structure, events, actions, and context to identify and explicate causal mechanisms [23]. The author's dissertation used a qualitative method to investigate in a case study of over of about 400-500 scientists (interviewed) sample working on rocket propulsion at Marshall SFC. Sample size was reduced in editing for relevance to the unit of analysis (i.e. combustion instability, CI).

Leveson et al, (2017) suggested that increased system complexity due to component-component interactions caused accidents and hazards, not chains of component failures leading to a loss (as probability-determined, in failure rates) [24]. Unknowing, unobserved mal-behaviors arise from component-component interactions, imperceptible at the system level, but manifest at a later timepoint as performance aberrations [25]. No matter how accidents and hazards due to system complexity occur, decision making control as a preventative measure lies with either the system user or the automated system controls. The imposition of machine logic that system automation affords, disorients system users who work from different rules of logic [26]. First, user tasks (e.g. device setup and initialization, configuration control, operating sequences) change from routine and standard to nonroutine tasks of problem solving [27]. Second, user cognition demands for system operations change, creating new human-machine interactions (HMI) for user tasks and attentiveness. Third, new technology couples with different system parts previously less connected [28] Based on documentary content analysis of interviews by Marshall's propulsion engineers, this case study operationalized a problem focus (i.e. CI) to a system management focus (i.e. of rocket engine complexity) and provided an experiential context of actual system usage that was both technology- and problem solving- driven. Contemporary approaches in problem solving research included (1) naturalistic scenarios to simulate and then identify inter-individual differences in how system users control dynamic system complexity and (2) well-defined systems of known properties in which to correlate user acquisition of new knowledge in response to manipulating system features [29].

Probability of project failure, measured by technical failure of performance as well as programmatic failure of cost and schedule [30] manifests from both observed and unobserved structures and inter-structural relations. Developing and incorporating sensor technology, especially with complex systems, entail distinct validation of technological readiness and reliability [31]. Propulsion data derived from either sensor-visualization methods or from testing provide the basis for developing a model to simulate real-world propulsion operational processes. Whereas sensor-visualization simulation models are data-driven, requirements engineering processes are model driven to enable model refinement and transformative platform model generation. Advanced power system visualization tools integrated with propulsion modeling methods synthesize data informative of propulsion problems and enable identification of timely corrective actions to ensure system reliability [32]. Solution of multi-objective optimization problems in aeronautical and aerospace engineering has become standard practice. The high technical risks involved, present opportunity to consider the problem domain of component-component interactions and identify requirements needed during the engineering process. TRL 5- TRL 6 transitions show increasing levels of systems-integrated solutions for progressing toward operational performance in mission-level scenarios. According to Pubic Law [33], technologies that are TRL 6 or better are considered as meeting minimum maturity level acceptable to system development (i.e., EMD) at Milestone B.



V-model by Bender 2005, translated from Bender (2005)

Bender's 2004 model divides system development into hierarchical levels [34]. Note that the separation of the different domains does not take place at the top of the model, but already at the level of the subsystems. [34]. Systemic risks due to system complexity of component-component interdependencies initiate cascades of emerging behavioral trajectories clustering toward a problem domain. They go beyond an agent-consequence analysis of a monocausal model of risk [35]

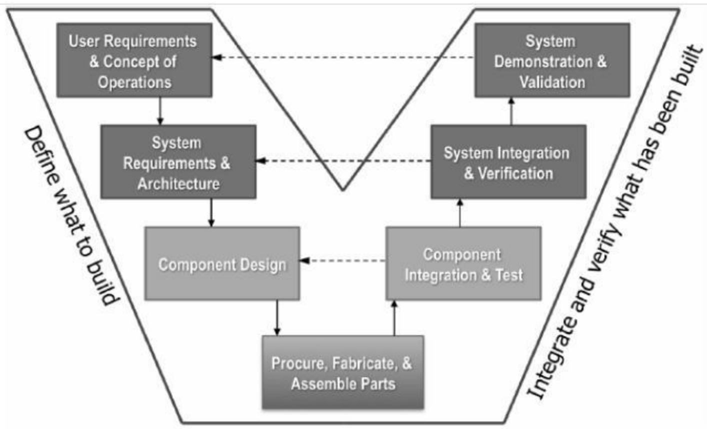


Fig. 1. Typical systems engineering V-model.

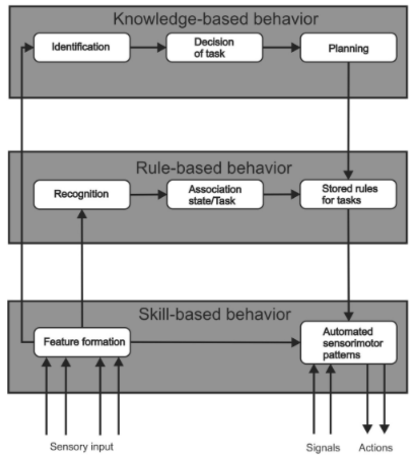
The V-model of VDI guideline 2206:2004 (Figure 1) basically divides the development process into three sections: The decomposition on the left side of the V-model describes the transformation of requirements, which are presented as an input, into a system design. This leads to the second section of engineering in different disciplines, the domain-specific design process. The third section integrates the disciplines on the right side of the V-model during the system integration, verification and validation. The result or output of the V-model is a product [36].

Task complexity. The feedback culture of project management updates user beliefs, values, and action patterns in a coordinated and interdependent manner as a mode of organizational change readiness for ongoing innovations [37]. With respects to system operations, feedback from problem solving experiences over time improves system designs to enable better technology task fitness [38]. Both operant learning and improved designs appreciate the value of technology innovation as evidenced by the performance impact resulting from system usage. In Rasmussen's SRK model, work domain analysis of actual system usage for problem solving was defined, but solutions were ultimately decided by stakeholders whose role was not defined. The current study sought answers to the following questions to characterize a comprehensive user-context that included stakeholder-KBB user relationships.

Q1. How does archival data describe the relationship between KBB-system users and stakeholders?
Q2. How does problem solving demand due to issues in system complexity affect system operations?
Q3. How does technology innovation affect the operational work domain of system users?

Technology utilized in complex systems' operations that render successful performance expectations [39] benchmarked the tasks that TTF (technology-task fitness) refers to. However, work tasks matched to the function domains of complex systems for performance output depended on user capability to problem-solve as well as suitability to manage complex operations per situational awareness. User TTF alignment with the actual system operating tasks, determined behavioral expectations as a predictor of system use, measurable in performance output [40]. To support task completion, users needed to display optimal HMI decision making capability, particularly in cases of task complexity and system complexity [41]. Therefore, understanding system complexity provides half the evaluative basis to determine the HMI fitness for system technology.

Internal structures organized around system complexity-task complexity relationships help inform the type of governance needed for problem solving activities. Internal governance may be characterized as either mechanistic or organic [42]. In mechanistic structures, three or more levels of governance manage decisions made. Close supervision of users and compliance with standard operating procedures are reasonable expectations; job duties are narrowly defined with non-overlapping tasks. In comparison, organic structures with fewer management levels provide for greater flexibility to utilize protocols and operating procedures as operative guidance for system usage, and user freedom to autonomously make decisions [43].

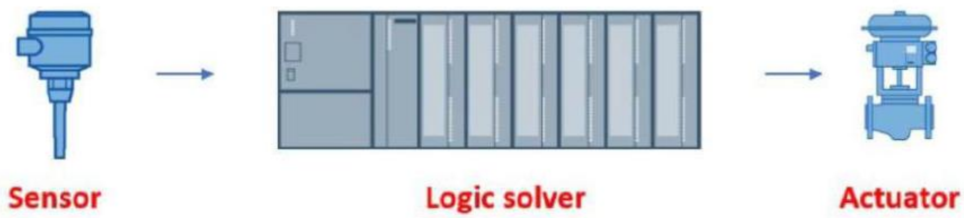


Rasmussen's SRK (skill-rule-knowledge) model
Rasmussen's SRK (skill-rule-knowledge) model (adapted from [44]).

Problem solving 1. Problem solving represents a critical form of system usage in terms of non-routine tasks. As a factor in the development of innovation capability, it remains an under-researched concept [45]. Unknowing, unobserved mal-behaviors from component-component interactions, imperceptible at the system-level, manifest at a later timepoint as performance aberrations [46]. Therefore, the if-then case scenario of ineffective feedback from SBB and RBB control strategies users employ to correct persistent faults in the system, prompts KBB- action planning with further evaluation of the changes undergone with the system's dynamic state [47]. Problem domains responsible for performance anomalies consist of sets of initial states and goal states of the system's operating condition, and their constraining paths of system functionalities in performance, complexity features in which system users find incomprehensible [48].

Performance output actualizes when operational tasks are system-engaged, not system-intended. Rasmussen's SRK model elaborated actual system usage. Without the characterization of user tasks, perceptions of system usage lack the experiential context for which system-/ task- complexities due to technological innovations are based [49]. Rasmussen's SRK model of generalized system usage (in terms of human operational controls) aligned with the hardware architectural hierarchy of sub-architectural levels (component-subsystem-system) in complex systems [50]. Thus, Rasmussen (1986) correlated usage abstraction to best support different modes of decision making and problem solving that aligned with distinct levels of system compositional complexity [51]. This enabled a work domain analysis (WDA) to identify design-affiliated knowledge structures, at aggregated system levels that users accessed and interfaced with By re-framing system usage in terms of HMI (and, technology task fitness, TTF), user cognitions of variable task complexity aligned with the innovation characteristics of system complexity[52]. However, the KBB-controls affected all the system levels. In addressing work domains of system- and operational- complexities per case study, KBB- users appeared verifiably more engaged with problem solving activities in comparison to SBB- and RBB-users.

Problem solving 2. Subsequent to the dissertational case study, system operational context was considered for a more autonomous scenario with limited astronautic HMIs. In such case for future study, the author deemed the importance of risk-informed decision-making (RIDM). Overall, RIDM and periodic risk assessments based on performance monitoring (multiple use of sensors and control feedbacks) of programmable systems enable detection of dangerous hidden faults in a Safety Instrumented System (SIS) composed of pressure systems, temperature systems, programmable logic controllers, and an actuator subsystem.



Generally, systems will not be put in operational service when their probabilistic risk assessment (PRA) indicates an unsustainable mission outcome. PRA of the environment monitors conditions that trigger SIS to initiate a safety function. In the event of lunar operative or functional vulnerability due to solar flares or coronal mass events, disruptive damage to spacecraft hardware or on-board satellite electronics would signal high risk of system failure and abort the on-orbit mission. Component information measurements (CIM) identify system weaknesses and inform prioritization of reliability improvement activities.[53]. The importance of interdependent network components with a resilience-focused performance measure suggests that: (i) CIMs quantify the effect of the disrupted components on the resilience of the interdependent infrastructure networks once they are recovered, and (ii) CIMs measure the potential impact on the resilience of the interdependent infrastructure networks caused by a specific disrupted network element. Resilience-based metrics of component criticality with respect to their influence on the overall resilience of the system (i.e. on the system's ability to quickly recover from a disruptive event) help prepare an efficient component repair checklist in the event of system failure. Natvig et al. introduced a dual extended measure for repairable systems; the components that are considered important are those whose repair significantly reduces the expected time of residence of the system in the worst states [54]. Hence, the dual Natvig measure is a resilience measure for multistate components in a multistate system [55]. Dui et al. introduced a cost-based integrated importance measure to identify the components or group of components that can be selected for preventive maintenance, and considered the effects that both cost and time of component maintenance have on system reliability [56]. By taking into account the time and order of recovery of the disrupted components, two resilience-based CIMs were proposed by Barker et al. [57]. The two CIMs respectively evaluated the impacts of the failure and invulnerability of an individual component during the time it took for the full network service was restored. In other words, resilience-based CIMs determined the effect of the disruption, rather than the restoration, of an individual component on network resilience. Implementing protection actions supports the integrity of components and subsequently improves network resilience. The resilience optimization approach therefore enables the cumulative recovery of functionality of a disrupted network to be maximized over a specific time span. Fang et al. proposed two metrics, i.e., the optimal repair time and the resilience reduction worth, to measure the importance of each component in a network [58]. Figure 2 shows three transition states with regards to the operation within a network. The first state is the original state, -., which is the state of the network from time / until the occurrence of a disruptive event, 0 at time /1. The second state is the disrupted state, -2, which is the state following the maximum disruption that occurred during the period (/1 , /2) and will last until the recovery process starts at time /3 . Finally, the third state is the recovered state,-4, which is the state of the network upon the completion of the recovery process at time /4. The performance of the network (e.g., flow, connectivity, or delay) across these different states over time is measured by the function 5(/),which describes the behavior of the network before the occurrence of a disruptive event, 5(/), after being disrupted,5(/2), and after being recovered to a desired level, 5(/4). Accordingly, network resilience Я characterizes the time-dependent ratio of the network recovery over the loss in its performance following a disruptive event (i.e., Я(/) =Recovery(/)/Loss(/)).

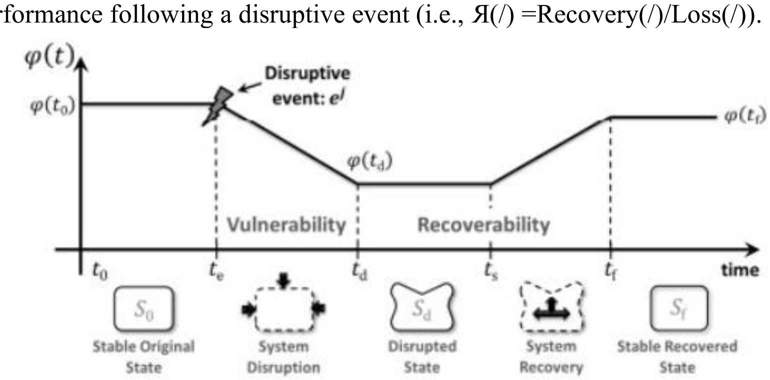


Figure 2. Illustration of network performance, + (,), across different transition states.

The variable development of the time-dependent system recovery results from the dynamic nature of service demand and system upgrading. The targeted system performance is not equally or uniformly affected by the disruption event. Additionally, various strategies exist for recovery activities, and system performance is ultimately a function of recovery decisions. The system resilience R(t) at time t (t > td) describes the cumulative system functionality that has been restored at time t normalized by the expected cumulative system functionality, assuming that the system had not been affected by disruption during the time period. The recoverability dimension of resilience and R(t) is in the range of [0, 1]. R(t) = 0 when F(t) = F (td) indicating no recovery from the disrupted state, hence no "resilience" action. R(t) = 1 when F(t) = F'(t) corresponding to when the system recovers to a target state.

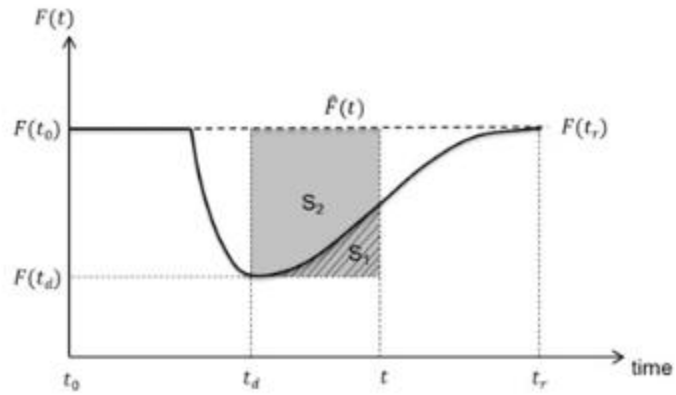


Figure 3. Conceptual illustration of the proposed resilience measurement

Resilience shows a progressive cumulative restoration of system functionality as well as both magnitude and rapidity of the system recovery [59].

Conclusion

Over a twenty year post-Apollo period, over half the launches failed due to propulsion subsystems. The high levels of complexity associated with propulsion subsystems as well as the need to lower propulsion development costs indicated an issue with readiness management of propulsion technology portfolios in system development projects. Since risk analysis and response planning should be done during the initial phase subsystem development, greater assessment and evaluation of the technological readiness was considered. Systemic risks due to the complexity of component-component interdependencies initiating cascades of emergent, nondeterministic behaviors clustering toward a problem domain described more of a problem with subsystem complexity independent of subsystem technology readiness maturity or lack thereof. An unpredictable operative subsystem performance suggested a case study approach to investigate not only the technical artifact interactions at the component level of system hierarchy but the context in which the system is observed operative. System operations indicate a performance metric as the outcome of system usage. And, system usage suggests sequential tasks enacted on system circuitry of switches for a multistate environment of system operations. HMIs alignment specific to hierarchical level system complexity shows a synchronous situational awareness that is either managed with skill-, rule-, or expert knowledge- based decision making, or a safety instrumented system of sensors, programmable logic solvers, and actuators. Several models of problem solving protocols including Rasmussen's SRK model manage performance of system operations. Alternatively, preventative models of problem solving aim for a more fractionated restorable functioning performance post-disruptive hazards. Resilience-based CIMs determine the effect of the disruption, rather than the restoration such that CIMs identify system weaknesses and inform selective prioritization of reliability improvement activities of an individual component on network resilience.

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