

Fundamentals of Agile Systems Engineering – Part 1

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Abstract

Agile systems-engineering and agile-systems engineering are two different concepts that share the word agile. In the first case the system of interest is an engineering process, and in the second case the system of interest is what is produced by an engineering process. The word agile refers to the adaptability and the sustainment of adaptability in both types of systems. Sustained adaptability is enabled by an architectural pattern and a set of system design principles that are fundamental and common to both types of systems. Research that identified this architectural pattern and design principles is reported, updated, and applied here in two Parts. Part 1 focuses on agile-systems engineering, reviewing the origins, values, and core concepts that define and enable domain independent agility in any type of system. Part 2 focuses on agile systems-engineering, identifying core agility-enabling concepts in the software-development domain-specific practice known as Scrum, reviewing an agile hardware/software satellite-development systems-engineering case for its source of agility, and then suggesting the development of an agile systems-engineering life cycle model as a natural next step.

Introduction

The value proposition of an agile system is rooted in risk management, providing options when system mission or system survival is threatened. Some might say the purpose or objective of an agile system is risk management, but natural agile systems exist without that purpose/objective, just that benefit. Most natural systems have evolved sufficient agility to sustain existence in the inherently risky environments that surround them. But nature doesn't care. Agility is a byproduct of natural selection, an algorithm without an objective (Dennett 1995), based on replication with variation in a competitive environment; an algorithm that unwittingly experiments with expendable resources over long periods of time. This method is generally not suitable to systems designed and built by man for purposeful objective, if these systems are to remain effective in an uncertain and unpredictable environment for a reasonable period of time. But we can learn from nature's experiments, perhaps improve upon their results, for nature finds sufficient but not necessarily optimal solutions.

Natural systems analysis is not the only path. We can also learn from man-made systems that exhibit the ability to survive, even thrive, in uncertain and unpredictable environments, and analyze these systems for common and replicable patterns that provide this capability. Intensively in the nineties, and continuously thereafter, well over 100 man-made systems exhibiting agile characteristics have been studied in workshops conducted at a wide variety of host sites, which

examined systems in many domains including manufacturing processes, enterprise processes, hardware systems, software systems (Dove 1993a; Dove et al 1995; Dove, Hartman, Benson 1996; Dove 1998; Dove 2001; Dove 2005), and more recently, development systems (Dove and LaBarge 2014).

This article summarizes the findings of those empirical studies, with the purpose of presenting in one document what appear to be necessary and sufficient fundamental architecture and design guidance for the systems engineering practitioner. The engineering usefulness of the architecture and supporting design principles have been confirmed by one of the authors in twenty five years of evolution and deployed employment, with examples in (Dove, Pirtle, Wilczynski 1987; Dove 2005; Dove 2009; Dove 2011), and in nine years of design and analysis projects conducted by masters students, with examples in (Bose and Dove 2010, Papke and Dove 2013).

Understanding the fundamental enablers of systems agility is timely. The pace of technology is reducing the useful lifetime of deployed systems and increasing the risk of long development programs. The pace of social collaboration on a global scale changes the effectiveness of government processes and increases the pace of technological and social innovation. The pace of global network dependencies of all kinds brings both benefit and vulnerability.

In the military, agility is sought in agile command and control (Alberts 1996, 2011), US force transformation (Cebrowski 2003), in composable force projection (Sillitto 2013), and in rapid acquisition and quick reaction capability (DSB 2009, SAF 2011). In commercial sectors agility is sought to sustain growth, innovation, and market leadership. In organizational support, agility is sought in service oriented architecture, web services, and cross organizational collaboration. In security, agility has been employed by the adversary to great effect for some time, prompting a growing voice for agile security systems.

Agility has been confusingly defined in the literature as various and overlapping system characteristics. Updating timeless core concepts developed in the '90s, this article presents a succinct core definition of agility; its relationship to various literature definitions; and the nature of uncertain, unpredictable, risky, and variable system environments that agile systems-capability is meant to address.

Loosely coupled modular systems are generally considered the core enabler of systems adaptability and flexibility in the literature (Orton and Weick 1990), but sustainability embedded in architecture has been largely ignored (with a notable exception in Weick 1999), as has the necessary core nature of infrastructure and resource pools, design principles, and methods for developing agile-response requirements. This article offers the practitioner means to address these issues.

Agility

In the 1980s the world conceded that the Japanese lean manufacturing concepts led to superior competitive manufacturing capability. Major manufacturers world-wide were scrambling to catch up. Charles Kimsey, in the Office of the Secretary of Defense, thought differently. He thought while everybody struggled to catch up, some effort also ought to be spent trying to identify what would be next, especially since the Japanese were already working toward a next paradigm, attempting to start what is now called the Holonic Manufacturing Systems consortia, investigating systems composed of holons: intelligent, autonomous, cooperative agents (Christensen 1994). Kimsey arranged to fund this look-ahead project at Lehigh University through the US Navy

Mantech program. Thirteen companies were invited to send appropriate thinkers to a summer-long workshop at Lehigh University, with the purpose of identifying an emerging problem so common and key to competition that it would become the next differentiator once lean was broadly diffused.

That problem was identified as the ability to respond effectively and with competence, to operational environments with increasing uncertainty and unpredictability (Dove and Nagel 1991, Dove 1992). That ability was named agility, and that study spawned the Agility Forum (nee Agile Manufacturing Enterprise Forum) to explore the nature of agile enterprise and domain-independent agile systems throughout most of the '90s. The primary focus of the 1991 study was on the agile manufacturing enterprise, not on manufacturing floor systems or processes as is often thought. The work in process was socialized widely for feedback with groups such as NIST, DARPA, the Defense Science Board, the Aerospace Industries Association, and others recognized in (Dove and Nagel 1991); which likely sparked subsequent military “agile enterprise” interests such as force transformation (Cebrowski 2003). The 1991 study identified the problem and developed agile-enterprise conceptual visions in four different commercial domains: automotive, process, semiconductor, and telecommunication industries. A subsequent Agility Forum study broadened the focus to agile systems of all kinds, and began the search and development of agile-system enabling fundamentals.

With the agile label and concept in play, Hewlett Packard was the first to initiate a program to educate its customers (Dove 1993a) and subsequently bring to market IT support under the Agile Enterprise banner; DoD’s Command and Control Research Program began an exploration of agile command and control (Alberts 1996) that continues today, and the Agile Manifesto for Software Development (Fowler and Highsmith 2001) adopted the agile label as appropriately descriptive and fundamentally consistent with their concepts¹.

So an enterprise focus came first, domain-independent agile fundamentals next, then an application to military force transformation, and then software development adopted the agile label with profound popular-awareness effect. Today the software development use of the label gets wide employment; perhaps because the software development community expressed a strong natural pull for a new development paradigm beyond waterfall on a large scale.

Tracking the history of the agile-systems fundamentals development effort, the 1991 publication of the 21st Century Manufacturing Enterprise Strategy (Dove and Nagel 1991) opened the door with strategic intent and vision, a call for action with little in the way of true guidance at that point. The next two years at the Agility Forum developed preliminary agile systems enabling frameworks, inspired by work in the late '80s on an object-oriented CAD-like product for developing factory-wide cellular control systems at a company called Flexis Controls (Dove, Pirtle, Wilczynski 1987). These frameworks were first published at the 1993 Defense Manufacturing Conference (Dove 1993b), fueling a subsequent five-year series of industry-collaborative workshop studies that involved some 1000 people and 250 organizations, who examined 100+ systems of all kinds (Dove 1994, 1998, Dove et al. 1995) which exhibited agile characteristics. During this same period an agile enterprise reference model was developed, which featured a capability maturity model and analysis process to measure how agile a company was in 24 different business practices (Dove, Hartman, and Benson 1996). The workshops and reference

¹ Personal communication with Jim Highsmith, a founder of the Agile Manifesto for Software Development (Fowler and Highsmith 2001).

model work refined and augmented the original frameworks, culminating in the publication of *Response Ability – the Language, Structure and Culture of the Agile Enterprise* (Dove 2001). Title notwithstanding, the book addresses systems within an enterprise, and was completed during the design and implementation of an enterprise-wide IT system that featured the first agile-ERP (enterprise resource planning) system; allowing each department to have ERP resources from any vendor, changeable at any time, all interacting as if from a single vendor. In 2001-2002 the development and implementation of this agile-ERP system was designed and managed as an agile development process (Dove 2005), with three successive three-month releases that each provided functional ERP operational capability to the company – on time and under budget.

In 2005 came a request to develop and teach two courses for an Agile Systems and Enterprises certificate at Stevens Institute of Technology – which has refined further the vocabulary and design processes which appear in collected form here. Working with practicing systems engineers pursuing graduate degrees and masters projects helps clarify the conceptual and operational stumbling blocks for the new initiate. In 2012 an INCOSE working group was chartered for Agile Systems and Systems Engineering, with a charter focus on applying and socializing the application of agile-system fundamentals to agile-systems design and agile systems-engineering, integrating these fundamentals with general Systems Engineering process concepts to explore the issues beyond Agile Software Development practices. It is anticipated that this working group effort will also return to the characteristics of agile systems beyond fundamentals, inspired by Alberts work and the recent work in resilient systems engineering. This present article is motivated by a need to provide a foundation of fundamentals for the working group activity; and to update the articulation, understanding and application of fundamentals arising from some eight years to date of teaching the architecture, enabling principles, and concepts of operations for agile systems creation.

Defining Agility

Words and phrases as labels for distinguishing system concepts have the ability to identify the core essence of the concept, and provide a valuable service in doing so. Example labels applied to system concepts of interest include lean, agile, resilient, composable, and many others. But as concepts become popular, their proponents often attempt to expand what they encompass to include related concepts, in what appears to be an attempt to unify everything of current interest under a single label of some personal or program interest. To be sure, there are many best practices shared among many legitimate labels, but they are applied specifically to augment and support the core essence of what entitles the label to represent a uniquely distinguishable concept.

In an invited synopsis paper of the 1991 Lehigh study (Dove 1992) defined agility as “that characteristic which allows an organization to thrive in an environment of constant and unpredictable change.” Similarly, the most extensive and thoughtful ongoing effort to operationalize agility started in 1996² with a military command and control focus, that has since matured into a broader focus on agile enterprise of any kind, military or otherwise (Alberts 2011), affirms that definition: “Agility is a capability that enables an entity to succeed in changing circumstances.” These overarching definitions are echoed equivalently in a variety of wordings for different domains, but consistently pinpoint the core definition of agile systems.

² The US DoD Command and Control Research Program (CCRP) has published a series of books about agile Command and Control beginning in 1996 with *Information Age Transformation* (revised in 2002), all of which are available for free download at www.dodccrp.org/html4/books_downloads.html

There is not a prescribed single way to express the definition of system agility, but however it is expressed, it should reflect the core concept as offered at the 1993 Defense Manufacturing Conference (Dove 1993b):

“We can adopt a working definition of agility as: The ability to thrive in an environment of continuous and unpredictable change. The focal point here is ‘change’ - the ability to initiate it, and the ability to respond to it. ‘Thrive’ is a key word because it implies both long term success, as opposed to a lucky response, and because it implies wielding agility both as an offensive as well as a defensive capability. ‘Continuous and unpredictable’ underscores the new long-term picture but, most importantly, distinguishes agility from mere flexibility, enabling successful change even when there is little advance notice and no prior expectation.”

A compatible version taught to systems engineering students emphasizes response effectiveness:

Agility is the ability of a system to thrive in an uncertain and unpredictably evolving environment; deploying effective response to both opportunity and threat, within mission. Effective response has four metrics: timely (fast enough to deliver value), affordable (at a cost that can be repeated as often as necessary), predictable (can be counted on to meet the need), and comprehensive (anything and everything within the system mission boundary).

As to the unpredictably evolving environment, emerging requirements are one typical and pervasive example in program and project management. In a more general sense, however, emerging requirements at both development and operational time are the only factor of interest, as all new response needs can be reduced to new requirements that should be addressed.

Core agreement on the agile definition notwithstanding, there is still confusion with other labels that appear to address some or all of the same capability: nimble, sense and respond, survivable, resilient, sustainable, autonomic, holonic, robust, and composable come quickly to mind. And of course there is the use of the agile label in Agile Software Development, which to many in the software and software-dependent fields is the exclusive understanding of what the agile label refers to and encompasses. Part 2 of this article will focus on agile systems-engineering, with both respect and perspective for the relevance of domain-specific agile software development practices to domain-independent agile systems-engineering.

Outside the scope of this article is an examination of each of these concept labels for core differences, overlaps, and identical meanings. But two labels warrant some attention: resilient and composable. Since the early agile systems work in the ‘90s, variations on the quad graphic of Figure 1 have been used to make the point that agility is composed of both reactive and proactive change proficiency. Since then, resilient systems have become a strong focus of interest and study, and more recently a call for composable systems is being heard. In both cases an ability to reconfigure system resources effectively to deal with new environmental situations is called for. As will be shown later, this ability to change effectively is enabled by a fundamental architecture common to both.

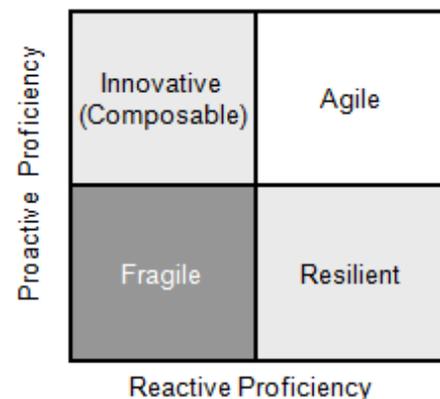


Figure 1. Two dimensions of response proficiency

Relating resilience to agility: Consolidating some 15 years of agile command and control

investigation for the US DoD, David Alberts recognizes resilience as one of six components (his word) of agile systems; and juxtaposes the definition with a need to respond to a “Change in Circumstances: The destruction, interruption, or degradation of an entity capability. ... Resilience provides an entity with the ability to repair, replace, patch, or otherwise reconstitute lost capability or performance (and hence effectiveness), at least in part and over time, from misfortune, damage, or a destabilizing perturbation in the environment (Alberts 2011: 217-218).”

Relating composability to agility: In a recent paper addressing military “composable capability”, Hillary Sillitto proposed: “...improved operational readiness, performance and interoperability can be achieved by applying a systems engineering methodology in which the ‘system focus’ is the force element, not the individual equipment; it is possible to identify a finite set of stable, well characterised building blocks (Force Elements) from which a wide variety of task force structures can be put together, providing almost infinite variety of capability solutions; ...” Sillitto suggests that the “System Coupling Model” (Lawson, 2010: 23) sets the context of “composability,” reproduced in Figure 2 as a condensed version of the agile architectural pattern shown later in Figure 3.

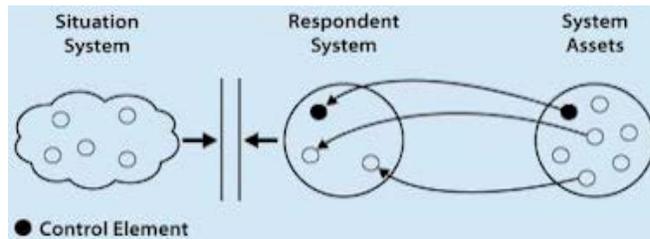


Figure 2. System-Coupling Diagram (Lawson 2010: 23) illustrating composability of a response system appropriate to a situation.

Effective response to both opportunity and threat is depicted in Figure 1 as response proficiency in two dimensions: proactive and reactive. As will be shown in the next section, an agile system’s response to a change in the environment, whether to take advantage of an opportunity or to respond to a threat, is achieved, metaphorically, by reshaping the system so that it is compatible or synergistic with the changed shape of the environment. A reactive response is a

compulsory systemic counter to a threatening change in the environment, with purpose to maintain or restore competitive functional performance. A proactive response is a non-compulsory systemic initiation enabled by a change in the environment, with purpose to improve competitive functional performance.

Metrics and Measures

How agile does a system have to be? Agility does not have a practical absolute measure, but is rather one of comparison to the dynamics of the environment, which includes competing systems that redefine acceptable performance requirements as they appear for the first time, and as they evolve.

There are four fundamental metrics for response proficiency: time, cost, predictability, and scope (Dove 2001: 70-87):

- Time to respond, measured in both the time to decide (after knowing) that a response is necessary, and the time to accomplish the response.
- Cost to respond, measured in both the cost of accomplishing the response and the cost incurred elsewhere as a result of the response.

- Predictability of response capability, measured before the fact in architectural preparedness³ for response, confirmed after the fact in repeatable accuracy of effective response.
- Scope of response capability, measured before the fact in architectural preparedness for comprehensive response capability within mission, confirmed after the fact in repeatable evidence of broad response accommodation.

These metrics do not stand alone, but work together. Having the capability to respond quickly, even instantly, does little good if the cost of response precludes the ability to respond again, unpredictably and as often as necessary. Predictability in effective response is the third metric, and the mark of a systemically repeatable response process. Finally there is scope, which differentiates agility from flexibility, and should encompass the ability to respond to anything within the system's mission space. A method for measuring an organization's response proficiency is explained and employed in an agile enterprise case study (Dove 1996).

The Environment Drives the Need

Agile systems are defined in counterpoint to their operating environments. Words used to describe the general nature of the target environment often include and combine dynamic, unpredictable, uncertain, risky, variable, and changing, with little attention to clear distinction among them. To design and develop a system that can deal effectively with changing environments it is useful to articulate the nature of changes that should be considered. A practice employed in classes and workshops on design methods for agile systems considers five types of environmental dynamics: caprice (unpredictability), uncertainty, risk, variation, and evolution. This categorization originated from a desire to explain why it felt natural to talk about agile systems as ones that can deal with uncertain and unpredictable environments. Is there a meaningful difference between uncertain and unpredictable – or was this just a lazy tendency to use two words when one can do?

Research yielded the wisdom of Frank Knight, who very carefully and logically separated the meaning of risk from the meaning of uncertainty in his 1921 doctoral thesis, subsequently published and still available as a delightfully readable classic economics book (Knight 1921).

Knight's work argues that random events come in two varieties, those with knowable probability and those with unknowable probability; and that this distinction separates risk and uncertainty. His knowable/unknowable distinction can also be a key differentiator for unpredictability and variation, though these do not have the symmetrical relationship of Knight's risk vs. uncertainty.

Our objective is a tool that directs the designers mind to a multidimensional exploration of response needs, consistent with the expectations of an agile system.

Agile systems have effective situational response options, within mission, under a CURVE framework:

- Caprice: randomness among unknowable possibilities.
- Uncertainty: randomness among known possibilities with unknowable probabilities.
- Risk: randomness among known possibilities with knowable probabilities.
- Variation: randomness among knowable variables and knowable variance ranges.
- Evolution: gradual (relatively) successive developments.

³ Architectural preparedness does not refer to a system's functional architecture, but rather to an underlying architecture which enables and sustains system's agility, discussed in the next section.

The difference between risk and variation in this framework is that risk is viewed as the possible occurrence of a discrete event (a strike keeps all employees away), while variation is viewed as the intensity of a possible event (absenteeism varies with the season).

Stated earlier, the value proposition of agility is risk management. Recently new thinking about risk is recognizing the role of uncertainty in addition to more traditional probability-based risk. For instance (Klinke and Renn 2002) describe precaution-based risk-management consistent with agile capability to deal with uncertain environments, while (Weike, Sutcliffe, and Obstfeld 1999) and (Aven and Bodil 2014) explore the management of risk with operational concepts that employ agile system concepts to sense and mitigate the sources of risk.

Agile Systems

Agile-systems engineering and agile systems-engineering are two different concepts (Haberfellner and de Weck 2005), but both rely on a common architecture to enable the agility in each. The architecture will be recognized in a simple sense as drag-and-drop, plug-and-play, loosely coupled modularity, with some critical aspects not often called to mind with the general thoughts of a loosely coupled modular architecture.

Agile systems are designed for change. They can be augmented with new functional capability. They can be restructured with different internal relationships among their subsystems. They can be scaled up or down for economic delivery of functional capability. They can be reshaped to regain compatibility or synergy with an environment that has changed shape. These types of changes are structural in nature, and require an architecture that accommodates structural change.

The focus in this article is on architecture, metaphorically the design of an instrument, and not on practice, the playing of that instrument. The second part of this discussion (Dove and LaBarge 2014) focuses on practice-enabling capabilities, while (Weike, Sutcliffe, and Obstfeld 1999) deal well with the operational practice aspects of awareness and action to employ these capabilities.

We are all very familiar with architectures that accommodate and facilitate structural change. Think of the construction sets we grew up with: Erector set, Tinker Toy, Lego, and Lincoln Logs. Just to name some of the classics. Each of these construction sets consists of different types of components, with constraints on how these components can be connected and interact. Though each construction set is better suited to some types of constructions than others, they all share a common architectural pattern.

Some, like Erector set with motors, can be employed to build active constructions such as Ferris wheels, helicopters, race cars, or simple robots. A Ferris wheel has a functional architecture, an Erector set has an agile architecture. The agile architecture enables the building and changing of the functional architecture. One could argue that the agile architecture is also a functional architecture, just in a different domain.

A system engineer tasked to design an agile system in some functional domain starts with the design of the erector set architecture for that domain. This agile architectural pattern is depicted in Figure 3 as applied to an Erector set, and explained subsequently in its general pattern sense. The standard graphic depiction pattern typically shows three sample system assemblies to indicate a range of configuration change.

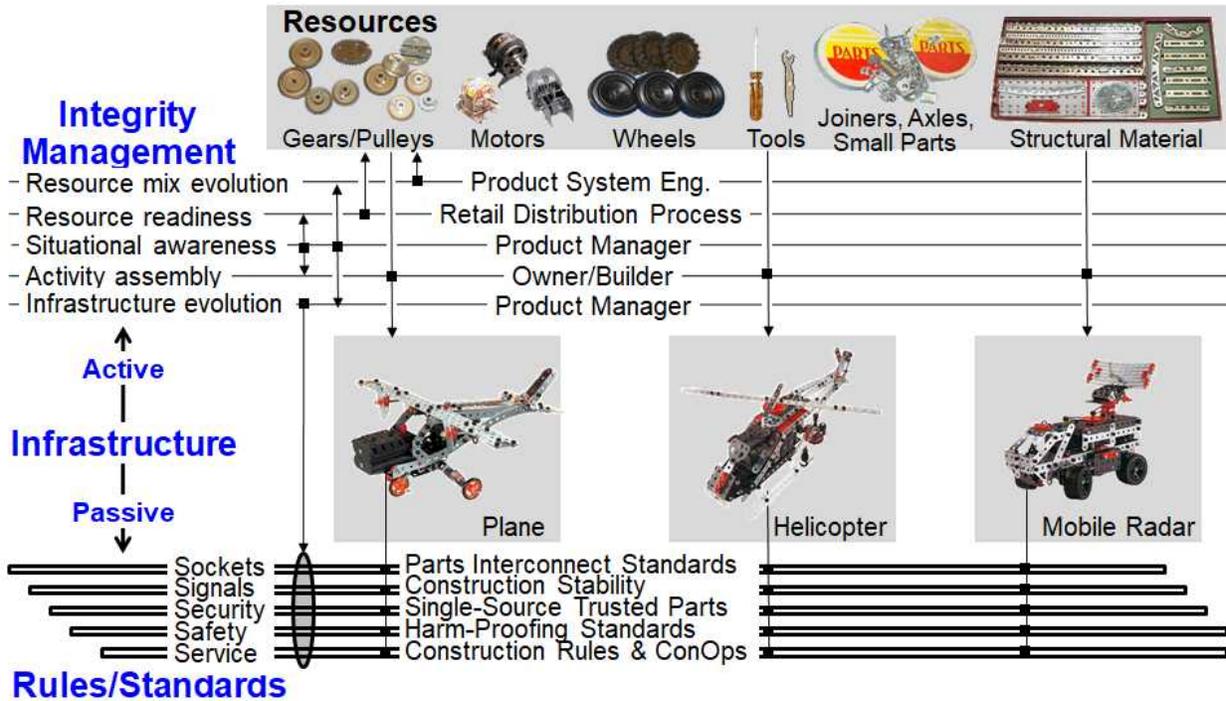


Figure 3. Agile architecture pattern depicting an Erector set construction kit example.

Agile Architecture Fundamentals

There are three critical elements in the agile architectural pattern: a roster of drag-and-drop encapsulated resources, a passive infrastructure of minimal but sufficient rules and standards that enable and constrain plug-and-play interconnection, and an active infrastructure that designates four specific responsibilities for sustaining agile operational capability. The coverage here of these elements is necessarily brief.

Here the word resource is generally used as a generic term for system functional assets, which can be human or inanimate.

- Resources—Resources are self-contained encapsulated units complete with well-defined interfaces which conform to the plug-and-play passive infrastructure. They can be dragged-and-dropped into a system of response capability with relationship to other resources determined by the passive infrastructure. Resources are encapsulated so that their methods of functionality are not dependent on the functional methods of other resources, except perhaps as the passive infrastructure may dictate.
- Passive Infrastructure—The passive infrastructure provides drag-and-drop connectivity between resources. Its value is in isolating the encapsulated resources so that unexpected side effects are minimized and new operational functionality is rapid. Selecting passive infrastructure elements is a critical balance between requisite variety and parsimony – just enough in standards and rules to facilitate resource connectivity, but not so much to overly constrain useful innovative system configurations. At least five categories of standards and rules should be considered: sockets (physical interconnect), signals (data interconnect), security (trust interconnect), safety (of user, system, and environment), and service (system assembly ConOps and evolutionary agility sustainment).

- **Active Infrastructure**—An agile system is not something designed and deployed in a fixed event and then left alone. Agility is most active as new system configurations are assembled in response to new requirements – something which may happen very frequently, even daily in some cases. In order for new configurations to be enabled when needed, four responsibilities are required: the roster of available resources must evolve to be always what is needed, the resources that are available must always be in deployable condition, the assembly of new configurations must be accomplished, and both the passive and active infrastructures must have evolved when new configurations and new resources require new standards and rules. Responsibilities for these four activities must be designated and embedded within the system to ensure that effective response capability is possible at unpredictable times. The “how” processes of dispatching responsibility should be articulated in the service element of the passive infrastructure.
 - **Resource Mix Evolution**—Who (or what process) is responsible for ensuring that existing resources are upgraded, new resources are added, and inadequate resources are removed, in time to satisfy response needs?
 - **Resource Readiness**—Who (or what process) is responsible for ensuring that sufficient resources are ready for deployment at unpredictable times?
 - **System Assembly**—Who (or what process) assembles new system configurations when new situations require something different in capability?
 - **Infrastructure Evolution**—Who (or what process) is responsible for evolving the passive and active infrastructures as new rules and standards become appropriate to enable next generation capability.

Agile Design Principles

Ten common Reusable-Reconfigurable-Scalable (RRS) design principles were discovered in workshop analysis of existing agile systems, and now are used to guide architectural design strategy. These principles are split into three categories, with the understanding that a principle in one category often provides benefit in the other categories. Need and intent are briefly outlined for each principle, with the “intent” providing a general strategy for meeting the need, and the understanding that an augmented or related approach may be a better fit to a specific-system need. Entire papers could be written on the variations and nuances of each of these principles. It is left to a designer’s creative insight to adapt the essence of the principle to the system of interest.

Reusable Principles:

- **Encapsulated Resources (Modularity)**—Need: System assemblers want effective resource replacement and internal change without side effects. Intent: Resources physically encompass a complete capability, and have no dependencies on how other resources deliver their capabilities.
- **Facilitated Interfacing (Plug Compatibility)**—Need: System assemblers want effective interfacing that facilitates integration and replacement of resources. Intent: Resources share minimal interface standards, and are readily inserted and removed.
- **Facilitated Reuse**—Need: System assemblers want effective resource selection and acquisition that facilitates reuse. Intent: Available resources are identified by capability and requirements, and can be readily discovered and acquired for deployment.

Reconfigurable Principles:

- Peer-Peer Interaction—Need: System assemblers want effective communication among resources. Intent: Resources communicate directly on a peer-to-peer basis to avoid intermediary relay failure, content filtering, and time delay.
- Distributed Control and Information—Need: System assemblers want effective information-based operational decisions. Intent: Decisions are made where maximal situational knowledge exists, and relevant information is maintained local to decision making resources while accessible globally.
- Deferred Commitment—Need: System assemblers want to maintain effective response ability. Intent: Conserve the commitment and consumption of limited resources to the last responsible moment, in anticipation of future unpredictable events and uncertain response needs.
- Self-Organization—Need: Systems assemblers want effective adaptation of interacting resources. Intent: Resource relationships are self-determined where possible, and resource interactions are self-adjusting or self-negotiated.

Scalable Principles

- Evolving Infrastructure—Need: System assemblers want effective acquisition and deployment of new resource capabilities. Intent: Passive infrastructure standards and rules are monitored for current relevance, and evolve to accommodate new and beneficial resource types in anticipation of need.
- Redundancy and Diversity—Need: System assemblers want effective resilience under quantitative (need more of something) and qualitative (need something different) situational variance. Intent: Duplicate or replicable resources provides quantitative capacity options and fault tolerance options; diversity among similar resources provides situational fit options.
- Elastic Capacity—Need: System assemblers want to incrementally match committed system resources to situational capacity needs of unpredictable or uncertain range. Intent: Resources may be combined in unbounded quantities, where possible, to increase or decrease deliverable functional capacity within the current architecture.

Response Requirements Guide Architectural Design

In addition to the system functional requirements, response situation analysis (RSA) identifies response requirements that inform the design and implementation of the agile architecture pattern. RSA indicates the necessary nature of resources and resource pools, which in turn identify the necessary nature of both passive and active infrastructure.

Requirements arising from RSA may not be directly present in customer requirements. Unlike functional requirements, typically captured in all-encompassing shall-statements, response requirements need only enumerate sufficient situational diversity to result in a capability that can respond to un-enumerated situations.

An effective framework for guiding RSA exercises drives analytical thinking in four reactive and four proactive domains. Note that response requirements should be stated as situations which arise during operation (the problem) that require a system response, independent of possible ways the

response might be satisfied (the solution). Solution strategies will change over time as new technology and knowledge become available.

Proactive responses are generally triggered internally by the application of new knowledge to generate new value. They are proactive responses even if the values generated are not positive and even if the knowledge applied is not new – self initiation is the distinguishing feature here. A proactive change is usually one that has effect rather than mere potential; thus, it is an application of knowledge rather than the invention or possession of unapplied knowledge. Proactive change proficiency is the wellspring of leadership and innovation in system capability.

Proactive domains:

- **Creation/Elimination**—What range of opportunistic situations will need resources assembled into responsive system configurations; what elements must the system create during operation that can be facilitated by resources and resource pools; what situational evolution will cause obsolescence of resources which should be removed? The distinguishing feature is the creation of something new or reincarnated that is not currently present. To note, this is not about the situation that calls for the original creation of an agile system, but rather about the evolution of the agile system during its operational period. Situations to identify are those that require system configuration assemblies during operation, and those that require new resources for employment in those assemblies.
- **Improvement**—What improvements in system response performance will be expected over the system's operational life? The distinguishing feature is performance of existing response capability, not the addition of new capability. Situations to identify are generally those involving competencies and performance factors, and are often the focus of continual, open-ended campaigns.
- **Migration**—What evolving technologies and opportunities might require future changes to the infrastructure? The distinguishing feature is a need to change the nature of the plug-and-play infrastructure, not the addition of new resources. Situations to identify are generally those that enable the transition to possible and potential next generation capabilities.
- **Modification (of capability)**—What evolving technologies and opportunities might require modification of the available resources and roster of resource pools? The distinguishing feature is a necessary change in available resource capabilities. Situations are generally those that require something unlike anything already present, or the upgrade or change to something that does exist.

Reactive responses are generally triggered by events which demand a response: problems that must be attended to or fixed, opportunities that must be addressed. The distinguishing feature is little choice in the matter – a reaction is required. Reactive responses are often addressing threatening competitive or environmental dynamics. They may also be responses to new customer demands, agility deterioration/failure, legal and regulatory disasters, product failures, market restructuring, and other non-competitor generated events. Reactive change proficiency is the foundation of resilience and sustainability in system capability.

Reactive domains

- Correction—What types of response activities might fail in operation and need correction? The distinguishing feature is a dysfunction or inadequacy during attempted response. Situations to identify are those that require a recovery from response malfunction, recovery from unacceptable side effects of a response, and inability to assemble an effective response.
- Variation—What aspects of operational conditions and resources vary over what range when response capabilities must be assembled? The distinguishing feature is predictable but uncertain variance. Situations to identify are those that manifest as variances in resource availability, resource performance, and resource interactions.
- Expansion/Contraction (of capacity)—What are the upper and lower bounds of response capacity needs? The distinguishing feature is capacity scalability. Situations to identify are those that can be satisfied with planned capacity bounds, as well as those that have indeterminate and unbounded capacity needs.
- Reconfiguration—What types of situations will require system reconfiguration in order to respond effectively? The distinguishing feature is the configuration and employment of available resources for new or reincarnated response needs. Situations to identify are those that are within the system mission boundaries, and that may require a reconfiguration of an existing system assembly, perhaps augment with removal of resources or addition of available resources.

An Agile System Example

The CubeSat Project originally set out to provide a low cost and condensed development time approach for very small satellites, affordable and suitable for university educational and research programs. The first CubeSat specification was developed in 1999 by California Polytechnic State University and Stanford University. While its original purpose was to help universities develop and test small, cost-effective satellites, the specification has also been used by commercial organizations and Governments around the world. By the end of 2012 over 75 CubeSats had been launched using 24 different launch vehicles (CubeSat 2012).

Key to the effectiveness of this program is its conformance to an agile architecture pattern from the start. Though the specification has evolved from lessons learned and open collaborative workshops over the years (Heidtl et al. 2000, Nugent et al. 2008), critical plug-and-play infrastructure specifications have remained stable to ensure plug compatibility of the deployment package (Figure 4) with a variety of launch vehicles, and plug compatibility of satellites with the deployment package.

The agile architecture pattern for CubeSat is shown in Figure 5. CubeSat satellites can be designed and built using a variety of modular components. Off-the-shelf chassis, power systems, communications, electronics, propulsion and sensor components are available from a number of different commercial providers. CubeSats can be deployed using a variety of launch vehicles and deployment systems.

The CubeSat design specification (CubeSat 2013) defines a set of physical, mechanical, electrical, environmental, safety, operational, magnetic, and test requirements for satellites. CubeSats can be made in three form factors: 10 x 10 x 10 cm, 10 x 10 x 20 cm, and 10 x 10 x 30 cm sizes, with a total weight of less than 5.0 kg. The small size and limited weight of a CubeSat enable “piggy back” launches, also called rideshares, to make use of extra space and lift capacity on third party launch vehicles. CubeSats are deployed using a Poly Picosatellite Orbital Deployer (P-POD), a standard deployment system developed by the California Polytechnic State University shown in Figure 4.

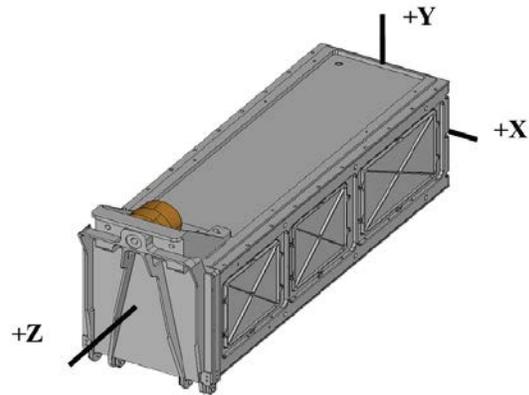


Figure 4. Poly Picosatellite Orbital Deployer (P-POD)

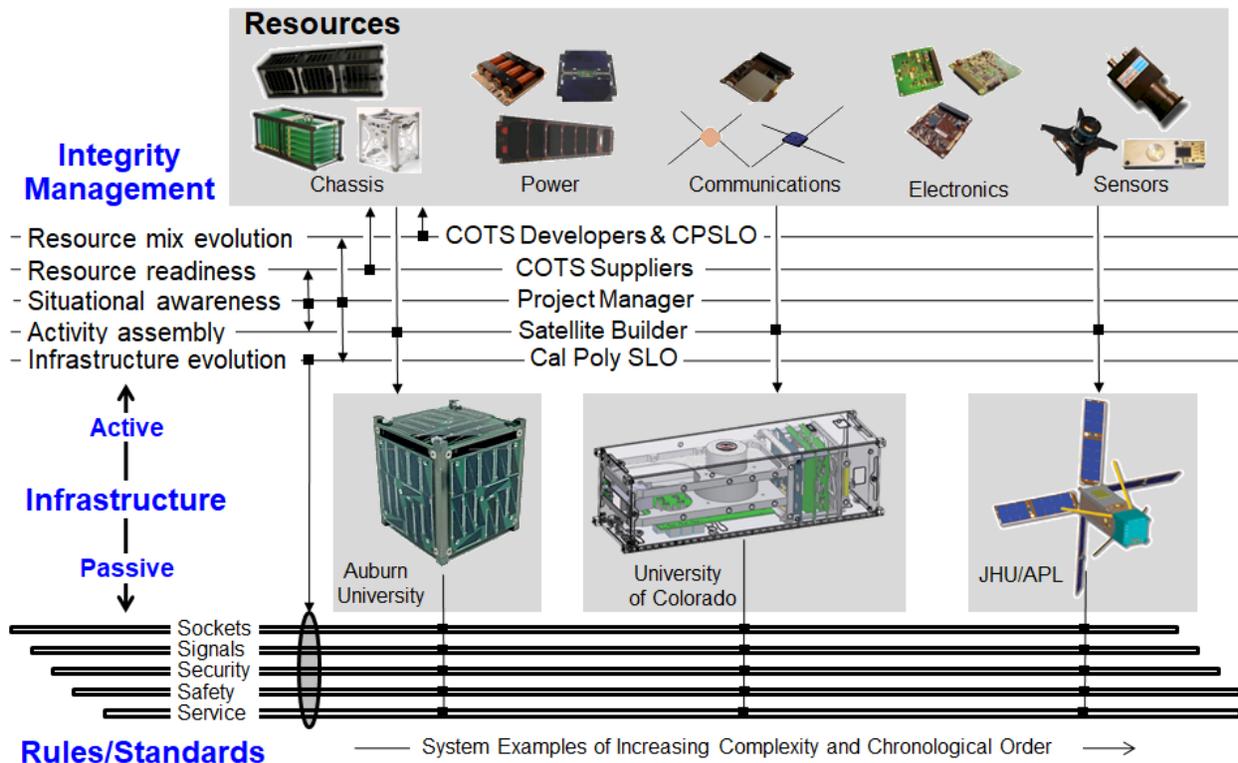


Figure 5. CubeSat Agile Architectural Pattern

The CubeSat specification includes a number of standards and requirements related to the P-POD deployment system, environmental standards for spacecraft launches, range safety, testing,

materials, and orbital debris. Launch vehicle operators may levy additional requirements on CubeSat developers in order to insure the safety of the launch vehicle, and other satellites that are to be deployed. In the past a variety of launch vehicles have been used to deploy CubeSats including Russian Kosmos-3M and Dnepr rockets, SpaceX Falcon 9 rockets, United Launch Alliance Delta II rockets, Orbital Science Minotaur IV and Antares rockets, and the International Space Station.

The active infrastructure of the CubeSat Project is supported through the international collaboration of over 100 universities, private companies and Government agencies responsible for the development of satellites. The system assembly role in the active infrastructure is played by universities, commercial organizations and Government agencies that are designing and developing CubeSats. On occasion these organizations may also play the role of resource mix evolution and resource supplier as they leverage their past experiences in developing CubeSats for future projects. The principal role players of resource mix evolution are COTS device developers plus the California Polytechnic State University as the developer of the CubeSat and P-POD specifications. More indirectly, launch vehicle operators and Government agencies responsible for licensing communications bandwidth affect resource mix evolution. A number of commercial vendors fill the role of resource readiness by providing a wide variety of off-the-shelf items that can be used to build a CubeSat. Finally, the role of infrastructure evolution falls principally to a team at Cal Poly San Louis Obispo (CPSLO) that publishes the evolution of design specifications (CubeSat 2013).

The passive infrastructure of the CubeSat Project is supported by the various specifications and standards that have been published by the California Polytechnic State University and others. The CubeSat specification defines a set of physical, mechanical, electrical, magnetic, and operational requirements that a satellite must meet in order to be plug and play compatible with the P-POD delivery system and the various launch vehicles. These specifications form the basis of the “Sockets” and “Services” portions of the passive infrastructure. The “Safety” portion of the passive infrastructure is supported by the combination of the CubeSat specification, a number of Government standards, and additional requirements imposed by launch vehicle operators. For example the CubeSat specification requires that satellites incorporate battery charge/discharge protection to avoid hazardous cell conditions that might endanger the launch vehicle or other CubeSats in the same P-POD. The “Signals” portion of the passive infrastructure is supported by the combination of the CubeSat specification and a set of Government regulations on the transmission of data using RF bandwidth. For example the CubeSat specification requires that CubeSat operators obtain and provide documentation of proper licenses for use of radio frequencies prior to launch. The only portion of the passive infrastructure that is not currently supported by the CubeSat Project is “Security”. The security of each CubeSat is left up to the developer and operator of the satellite.

Conclusion

This article is Part 1 of a two part article on agile systems engineering. This part deals with agile-systems engineering, a necessary precursor for understanding agility in agile systems-engineering, as an agile systems-engineering process is itself an agile system.

Unique to this article is the historical review of agile system definition, research, and concept development; and the recognition of David Albert’s extensive work in Agile C4I and military enterprise as compatible. Also unique, but intended as the practitioner’s take-away, is the model

of agile-systems engineering as the engineering of a system construction kit; the introduction of the CURVE framework; the updated and augmented articulation of the agile architectural pattern, the ten agile system design principles, and the eight response situation analysis domains. The introduction of the CubeSat agile system example in this article will play a role in Part2, when the agile systems-engineering process at John Hopkins University Applied Physics Laboratory (JHU/APL) for developing CubeSats is examined in some detail.

Part 2 of this article will suggest a parallel between Peter Checkland's Soft Systems Methodology and the situation faced when an agile systems-engineering process is appropriate; introduce a life cycle framework for agile systems-engineering; employ the fundamental agile concepts of Part 1 to examine the source of agility in the process known as Scrum for managing agile software development; employ the Part 1 fundamentals to examine JHU/APL's agile systems-engineering process for developing CubeSat hardware/software systems; and finally, suggest a method for developing a domain-independent agile systems-engineering life cycle model.

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Biography

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Fundamentals of Agile Systems Engineering – Part 2

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Revision 20-May-2018 made corrections and updates, changing UURV framework to CURVE, and modules to resources.

Abstract

Agile systems-engineering and agile-systems engineering are two different concepts that share the word agile. In the first case the system of interest is an engineering process, and in the second case the system of interest is what is produced by an engineering process. The word agile refers to the adaptability and the sustainment of adaptability in both types of systems. Sustained adaptability is enabled by an architectural pattern and a set of system design principles that are fundamental and common to both types of systems. Research that identified this architectural pattern and design principles is reported, updated, and applied here in two Parts. Part 1 focuses on agile-systems engineering, reviewing the origins, values, and core concepts that define and enable domain independent agility in any type of system. Part 2 focuses on agile systems-engineering, identifying core agility-enabling concepts in the software-development domain-specific practice known as Scrum, reviewing an agile hardware/software satellite-development systems-engineering case for its source of agility, and then suggesting the development of an agile systems-engineering life cycle model as a natural next step.

Introduction

An agile systems-engineering process is itself a system, gaining its agility from a fundamental architecture and set of design principles that enables adaptability. This architecture and set of design principles were the subject of a companion article of the same name, but designated as Part 1 (Dove and LaBarge 2014), with its focus on agile-systems engineering. A brief review of Part 1 will set the stage for applying the architecture and design principles to an agile systems-engineering process, the focus of this Part 2 continuation.

Agile-Systems Background

Agility is defined as the ability of a system to thrive in an uncertain and unpredictably evolving environment; deploying effective response to both opportunity and threat, within mission. Effective response has four metrics: timely (fast enough to deliver value), affordable (at a cost that can be repeated as often as necessary), predictable (can be counted on to meet the need), and comprehensive (anything and everything within the system mission boundary). This is a core definition of agility exhibited by an agile systems engineering process, as well as an agile system developed by any process, agile or not.

Explained in Part 1, agile systems are designed in counterpoint to their operating environments, characterized as a Capricious, Uncertain, Risky, Variable, Evolving (CURVE) framework:

- Capricious: randomness among unknowable possibilities.

- Uncertain: randomness among known possibilities with unknowable probabilities.
- Risky: randomness among known possibilities with knowable probabilities.
- Variable: randomness among knowable variables and knowable variance ranges.
- Evolving: gradual (relatively) successive developments.

Research that began in 1991, originating the concept of agile systems and putting the word *agile* into play, examined a large number of diverse systems throughout the '90s that exhibited agile capabilities. This research abstracted core architecture and design principles that appear necessary and sufficient to enable agility in systems and processes of any kind (Dove 2001). The architecture will be recognized in a simple sense as drag-and-drop, plug-and-play, loosely coupled encapsulated modularity, but with some critical aspects generally ignored in descriptions of modular architecture.

Agile systems are designed for change. They can be augmented with new functional capability. They can be restructured with different internal relationships among their constituent systems or subsystems. They can be scaled up or down for economic delivery of functional capability. They can be reshaped to regain compatibility or synergy with an environment that has changed shape. These types of changes are structural as well as functional, and require an architecture that accommodates structural change, whether the system of interest is a development process or the product of a development process.

There are three critical elements in the agile architectural pattern: a roster of drag-and-drop encapsulated resources, a passive infrastructure of minimal but sufficient rules and standards that enable and constrain plug-and-play interconnection, and an active infrastructure that designates four specific responsibilities for sustaining agile operational capability: resource evolution, resource readiness, system configuration, and infrastructure evolution.

Agile Systems-Engineering Context

Systems engineering is a disciplined activity that delivers engineered solutions to problems and opportunities – an activity often involving multiple stakeholders, coordination across multiple engineering disciplines, and complexity in both problem and solution (Sheard 2000). Unlike other engineering disciplines that employ natural laws to guide and govern engineering design with certainty within a single discipline, systems engineering deals with the social, political, and technical aspects of managing projects that span multiple disciplines. These projects can be quite large and complex, need cross-discipline unifying architectures and operational concepts, require multi-party accommodations to resolve tradeoffs, and often exhibit unexpected emergent behaviors as the project progresses.

Peter Checkland, in speaking of “hard” and “soft” systems thinking (Checkland and Holwell 2004, 45-46), characterizes the “hard” variety as classic systems engineering “appropriate in well-defined problem situations in which well-defined objectives are accepted and the live issues concern how best to engineer a system to meet them. ... On the other hand, ‘soft’ approaches are said to be appropriate in messy problem situations, characterized by obscure objectives and multiple clashing viewpoints.” Checkland’s Soft Systems Methodology (SSM), designed to learn and find effective responses to real world changing problem environments, has valuable and practical application in an agile systems-engineering life cycle model; but that pursuit is outside the scope of this current article. Much of SSM, however, is the (unrecognized) foundation of the agile software development management process known as Scrum, which will be explored later.

In agile systems-engineering, defining a solution in terms of the problem understanding and defining the problem in terms of the solution understanding is a spiral iteration of discovery and learning convergence through an evolving engineering environment. If the operational environment for the deployed system is also evolving, systems development continues beyond the development and production stages all the way to retirement, and benefits if the system produced is itself an agile system that facilitates continued change and adaptation.

Illustrated in Figure 1, the separate environments of both the engineering system and the engineered system define the needs and degrees for agility in each of those systems. If the engineering environment is not stable and predictable, an agile approach is appropriate; which will evolve

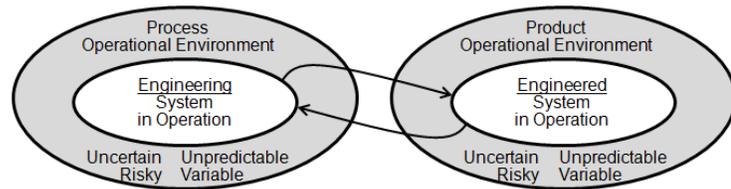


Figure 1: Two different operational environments defining necessary agile counterpoint for the systems they encompass.

engineered system variations, creating a dynamic requirements environment for the engineered system, at least during development. There is an interaction between both of these systems during development, as the engineered system matures in modeling, simulation, and prototype instantiations that provide feedback analysis to the engineering system. That process should continue throughout the remainder of the engineered system's life cycle if it is deployed in a dynamic evolving environment. Of course, the engineered system's life cycle may be cut disappointingly short if it is not designed and sustained as an agile system.

Agile Systems-Engineering and the System Life Cycle

Here the focus is on domain independent agile systems-engineering, a type of systems engineering distinguished by its ability to deliver functional system-engineering value in a dynamic systems-engineering environment.

Life cycle, as a term applied to systems, traditionally demarcates the progressive maturity flow of a system through a linear sequence of stages, from concept to disposal. Inherent in this model are the notions that a system is in one and only one stage at any point in time, and progresses from one single-state stage to another in a proscribed sequence.

For practical purposes one cannot argue with the notion that there are times when a system does not exist that bound a time when a system does exist. Nor can one argue against the necessity to develop a system before utilization can occur. Here, however, the argument is against the continued notions of non repeating stages and of single-state existence by depicting an agile life cycle in Figure 2 as having progressively concurrent repeated stages.

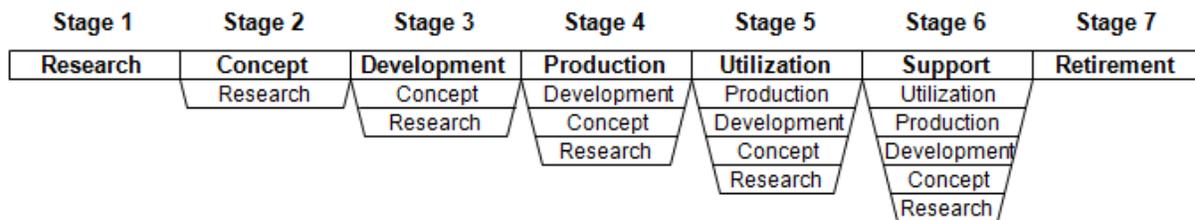


Figure 2: Framework of agile system engineering life cycle model, depicts constant evolution of all prior ISO/IEC 15288 life cycle stages as the life cycle progresses through maturity

ISO/IEC 15288 describes “the” generic system life cycle as a seven stage maturity process progressing through: exploratory research, concept, development, production, utilization, support, and retirement (ISO/IEC 2008, 10-14). This is a classic waterfall model at the macro level, with 15288 recognizing that each stage can be further reduced into maturity flows as well, which may or may not be waterfall models.

In reality, the 15288 stages of utilization and support are typically concurrent. Also, in reality, all stages are not necessarily true conditions of the system, but rather perceptions and/or claims of an individual or collective authority.

Looking at just two of the stages reveals the issue: must a system be either in a state of development or a state of utilization, but not both at the same time? A resilient system exists by definition in this dual state. So do agile systems, self-organizing systems, autonomic systems and other such dynamic systems that exist sustainably in an uncertain and unpredictable environment. Think of a city as a system, and consider that the subsystems of that city are many, are individually in a full variety of the different stages, and each typically moves among all of the different stages repeatedly over time.

Figure 2 shows a sequential system engineering maturity transition across the primary stages, but also recognizes that within each of the sequential primary stages is a growing concurrency of all of the prior stages. Agile systems engineering processes, by definition, are capable of responding to their environment as their environment changes, regardless of why or when these changes occur. Note that an agile systems engineering process has difficulty exercising agile capabilities if it does not develop an agile system, one that has an architecture which facilitates justified change throughout the development and subsequent utilization and support stages.

Each of the seven stages of the systems-engineering life cycle may have individually different operational environments, ranging from stable to unpredictable. Dealing with stage-specific agile needs and methods is beyond the scope of the current article.

In the domain context of agile software development, the production stage is the first build/release stage that puts product into the operational user environment, initially – not as a temporary prototype, but as a usable working product. Subsequent increments and iterations of development occur during utilization and support of prior releases.

An effective agile systems engineering process must converge on sufficient completion of each of the primary stages to warrant the transition to the next primary stage, presumably on schedule and on budget regardless of how flexible or rigid these might be. This is represented in the Figure 2 life cycle depiction showing diminishing emphasis on the lower concurrent stages as maturity through primary stages progresses.

The software-development management process known as Scrum is examined next; both because it is strongly associated with agile software development, and because it has excellent concepts that can be adapted to domain independent agile systems engineering, if these concepts are understood for how and what they contribute to agility.

Baseline Scrum

Scrum is one of the most popular project management practices for agile software development, and is highly associated with the concept of agile systems-engineering and the word agile in many people’s minds unfamiliar with agile concepts outside of the software domain. Consequently, the classic Scrum process will be examined as described in (Schwaber and Sutherland 2013) as a base

line for what makes it a truly agile process in the software development domain. The reader familiar with agile software development practices is advised that neither the Agile Manifesto's four concepts nor its 12 backup principles are responsible for the agility of the Scrum process, as will be shown. These concepts and principles are instead among well known (but not necessarily practiced) best project management practices and human productivity amplifiers, regardless of whether an agile systems-engineering (or agile software development) process is called for.

Overview of Classic-Scrum

In deference to readers that may not be versed in the Scrum process, as well as those that are unfamiliar with The Scrum Guide (Schwaber and Sutherland 2013), key elements are reviewed here, with quoted remarks in this section taken from that guide.

“Scrum (n): A framework within which people can address complex adaptive problems, while productively and creatively delivering products of the highest possible value.”

“Scrum is founded on empirical process control theory, or empiricism. Empiricism asserts that knowledge comes from experience and making decisions based on what is known. Scrum employs an iterative, incremental approach to optimize predictability and control risk. Three pillars uphold every implementation of empirical process control: transparency, inspection, and adaptation.” Scrum is an engineering process that works toward a solution in a series of steps, questioning the progress and process at the completion of each step. This requires complete transparency of everything that has been decided and accomplished, objective assessment of the quality and value of what has been accomplished and how it has been accomplished, and continuous feedback learning that adjusts both process and product to minimize variance from goals.

“Scrum's roles, artifacts, events, and rules are immutable and although implementing only parts of Scrum is possible, the result is not Scrum. Scrum exists only in its entirety and functions well as a container for other techniques, methodologies, and practices.” In the systems engineering perspective, Scrum is a management process architecture that can accommodate a wide variety of technical processes.

“Scrum Teams deliver products iteratively and incrementally, maximizing opportunities for feedback. Incremental deliveries of ‘Done’ product ensure a potentially useful version of working product is always available.” In Scrum an increment is called a *sprint*, and multiple sprints are construed as iterations on increments. Unlike Alistair Cockburn's (Cockburn 2008) well written distinction between increments and iterations, Scrum iterations typically add new features as well as improve the performance of existing features.

“The heart of Scrum is a Sprint, a time-box of one month or less during which a ‘Done’, useable, and potentially releasable product Increment is created. Sprints have consistent durations throughout a development effort. A new Sprint starts immediately after the conclusion of the previous Sprint.” Note that Sprints have consistent time durations, which establishes a cadence to the total project; and a Sprint ends when the allotted time duration expires, whether or not all work planned for the Sprint is completed. This hard stop is intended to improve the task and Sprint estimation capabilities of the developers. Unfinished work can be picked up in a subsequent Sprint.

“Scrum is a framework for a project whose horizon is no more than one month long, where there is enough complexity that a longer horizon is too risky. The predictability of the project has to be controlled at least each month, and the risk that the project may go out of control or become unpredictable is contained at least each month.” The time horizon resolves uncertain requirements

with a series of small investments in experimental development, evaluation learning, and adaptive correction if necessary. The allowable time horizon is a measure of the estimated uncertainty appropriate for a Scrum approach. The intent is to affordably contain the costs of incremental learning and correction.

“Scrum users must frequently inspect Scrum artifacts and progress toward a goal to detect undesirable variances. ... If an inspector determines that one or more aspects of a process deviate outside acceptable limits, and that the resulting product will be unacceptable, the process or the material being processed must be adjusted. An adjustment must be made as soon as possible to minimize further deviation. Scrum prescribes four formal opportunities for inspection and adaptation.” These are called the Sprint Planning Meeting, the Daily Scrum, the Sprint Review, and the Sprint Retrospective. All four are collaborative learning events with all team members present and participating.

“Optimal Development Team size is small enough to remain nimble and large enough to complete significant work. Fewer than three Development Team members decreases interaction and results in smaller productivity gains. ... Having more than nine members requires too much coordination. Large Development Teams generate too much complexity for an empirical process [learn by doing and evaluating] to manage.” This suggests the sweet spot for participative collaborative-learning diversity that spurs productivity lies between three and nine. Larger projects are then composed of multiple Scrum teams often organized as a Scrum of Scrums.

Shown in Figure 3, Scrum includes three major roles, four formal types of meetings, and two formal project management artifacts in an incremental and iterative framework (Sutherland and Schwaber 2007).

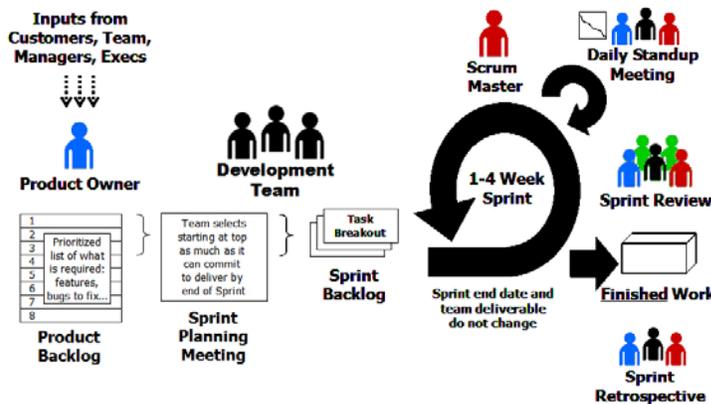


Figure 3. Scrum (from Sutherland and Schwaber 2007)

The three major Scrum roles are the Product Owner, the Scrum Master, and the Development Team. The Product Owner is responsible for defining, communicating, and prioritizing the product development tasks; and for accepting or rejecting the incremental product delivery at the end of each Sprint. The Scrum Master is responsible for ensuring that the Scrum process is understood, and that the practice adheres to Scrum theory and rules;

and will also train and coach the Scrum process. The Development Team is a self-organized, cross-functional group that performs the product design, development, integration, test, and demonstration tasks for each Sprint; and they are solely responsible for choosing how to accomplish these tasks.

The four formal meetings are Sprint Planning, Daily Scrum, Sprint Review, and Sprint Retrospective. With the exception of a fixed 15-minute Daily Scrum, these meetings are time-boxed relative to the duration of a Sprint, with times that follow shown for a 4 week Sprint. The Sprint Planning meeting timed at eight hours has two roughly equal parts: 1) the Product Owner

explains the tasks in the Product Backlog and their priorities, from which the Development Team decides how many of the high priority tasks to move into the Sprint Backlog, and 2) the Development Team then collaborates to agree amongst themselves on how they will complete the tasks in the Sprint Backlog during the next Sprint. The Daily Scrum is a fixed 15-minute meeting designed to quickly assess and resolve the state of the current Sprint as each Development Team member answers three critical questions: what did I accomplish yesterday, what am I planning to accomplish today, and what impediments are in my way? The Sprint Review meeting timed at four hours occurs at the end of the Sprint in two roughly equal parts: 1) the incremental product is demonstrated to the Product Owner, and 2) there is a discussion of positive and negative development-related lessons learned that can help subsequent Sprints. The Sprint Retrospective is timed at three hours and occurs after the Sprint Review and before the next Sprint Planning meeting, and examines how the Sprint went relative to people, relationships, process, and tools; identifying what went well and what needs improvement; and creating a plan for improving how the team does its work. With the exception of the Sprint Planning meeting, Scrum meetings are assessment, learning, and adaptation focused.

The two formal project management artifacts are the Product Backlog and the Sprint Backlog. The Product Backlog is a prioritized list of requirements, expressed as tasks that can each be implemented within the time-box limitations of a single Sprint; with complex tasks broken down into a series of sub-tasks that can be incrementally completed over several Sprints. The Sprint Backlog is a collection of specific design, development and test activities allocated to the current Sprint in process or about to start. Other less formal artifacts are typically used to monitor progress during a Sprint, such as the so-called Burndown Chart, which displays daily updates of the estimated remaining work hours required to complete the Sprint.

Interpretation of Classic-Scrum

Scrum is a discipline based on feedback learning, designed to remove uncertainty and risk about the system to be engineered, and designed to increase productivity of the engineering process. The learning occurs in fixed-schedule periodic assessments and adaptations, with feedback functioning much like a thermostatic control system uses negative feedback to reduce temperature variance from a set point. This feedback learning is intended to evolve both the engineered product and the engineering process in successive Sprints, with fitness feedback at Sprint Reviews and Sprint Retrospectives, much like natural selection evolves a species through successive generations. The value of this approach is completely dependent upon the quality of the Review and Retrospective objectivity and scope. The Scrum Master is responsible for the level of achieved quality or lack thereof in this feedback learning approach. Going through the motions with marginal benefit has little if any value.

Evolutionary learning happens between Sprints, real-time learning happens during Sprints. Real-time learning is the function of the 15-minute Daily Scrum meeting. Every participant in this meeting provides personal status in three areas: what I did yesterday, what I'll do today, and what impedes my progress. The value here is realized in what is heard and processed by others. Going through the motions without active collective listening provides no value. Again, it is the Scrum Master's responsibility to ensure this meeting's effectiveness.

Scrum raises the team's collective system-wide awareness and reveals unpredictable emergent behaviors, potentially revealing undesirable emergent futures before they occur.

The explicit essence of successful Scrum is *effortful* learning through active collaborative communication. Effortful learning is a self-motivated process that continuously identifies the next thing to learn after successfully accomplishing the last learning objective. In the case of a Scrum team, effortful learning is a key focus and responsibility of a competent Scrum Master.

The implicit essence of successful Scrum, however, is the ability to effectively adapt the process and the product to what has been learned. This means changing what is being done in product development and changing how it is being done in the team’s working process – which requires an agile (adaptable) architecture of both product and process to be effective. Though absent from the explicit principles and processes of Scrum, ensuring that agile architectures underlie both product and process are key responsibilities of the Product Owner.

You don’t hear the dependence of successful Scrum on agile architectures explicitly called out in the Scrum Guide or the Scrum Papers. Perhaps, on the product side, this is because Scrum was born and lives to solve software development problems in a time when software development employs Object Oriented Programming (OOP) techniques, which inherently provide the basic necessary structural needs for system adaptability – drag-and-drop modularity in a plug-and-play infrastructure. Thus, replacing, augmenting, or reconfiguring elements of software systems in successive Sprints is facilitated as learning drives adaptation. As will be shown in the next section, hardware product systems can also facilitate adaptation of Scrum-learning with an agile product architecture.

On the process side, Scrum theory and practice do not explicitly address the active infrastructure process management responsibilities necessary to sustain agility in the process architecture. Figure 4 assigns the architecture’s four active-infrastructure responsibilities to appropriate parties employed in Scrum. The process resources are principally the people. The competence quality of

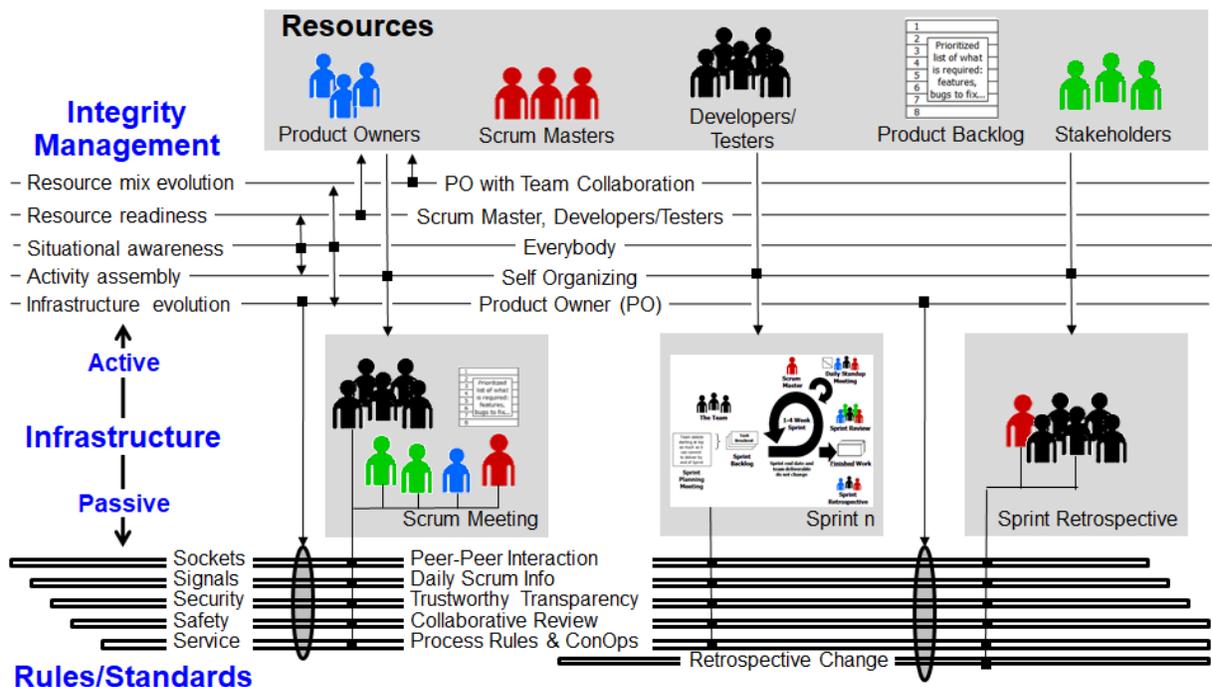


Figure 4. The Scrum Agile Architecture Pattern

Product Owners, Scrum Masters, and Developers are critical for obtaining and sustaining the benefits of the Scrum process. The Product Owner in this depiction is charged with the responsibility of staffing, assessing, re-balancing, and evolving the human components in the Scrum system. The Scrum Master in this depiction appears as a resource, appears in the active infrastructure as the system assembler, and appears in the passive infrastructure as the enforcer of plug-and-play resource interconnectivity standards.

Scrum is a proactive initiative, productively confrontational in nature. No denial is possible when Scrum is done right. It is highly intense in the people interaction area. The Scrum Master is the process coach and enforcer, as well as the “servant leader” enabling team productivity.

When is Scrum, or something like it, the right approach? When the team has little experience working together, when the problem and solution pair are insufficiently understood, when the emergent behavior of interaction complexity can produce unpredictable costly results, when the system and/or process environment are likely to evolve unpredictably, when stakeholder commitment to budget and schedule are uncertain. “Scrum is a framework for a project whose horizon is no more than one month long, where there is enough complexity that a longer horizon is too risky. The predictability of the project has to be controlled at least each month, and the risk that the project may go out of control or become unpredictable is contained at least each month.”

What if the Scrum Master and Product Owner are not what is required to reap the Scrum benefits? In such cases this contributes to dissatisfaction with the process among the participants, and with disappointment with the process among management. Experience has shown that many adoptions of the Scrum process are dissatisfying disappointments (Sutherland 2007, 79). However, in some cases Scrum provides a management framework that can be better than what it replaces even if it doesn't deliver much of the Scrum learning and adaptation potential. In these later cases it offers prescriptive shared procedure where perhaps none was present before.

An Agile Systems-Engineering Example

The CubeSat program introduced in Part 1 defines an agile-system architecture for developing and constructing CubeSats from a combination of community-available common-off-the-shelf components and internally-developed mission-specific components. The CubeSat agile-system architecture specifies internal plug-and-play infrastructure for satellite construction and external interfaces for launch-vehicle compatibility. The internal infrastructure specification enables agile mission-specific designs that can avoid the cost of architecture and infrastructure design, take advantage of widely available COTS resources, and focus development on mission-specific resources. The external interface specification ensures that any CubeSat can be deployed by any member of a conforming launch-vehicle family, providing agility at the higher mission-deployment system level as well.

CubeSat specifications say nothing about the system-engineering process that will develop and assemble a mission specific CubeSat at any of the many organizations that do these projects. Given the financial and window-of-opportunity risks associated with terminal deployment of a system that cannot be returned for replacement, correction, or design update, a common systems-engineering process would likely be some variation of a traditional waterfall engineering process, with big upfront planning and design.

A group at Johns Hopkins University Applied Physics Laboratory (JHU/APL) thought differently. Maybe because they had to. Quoted statements in this section, if not otherwise credited, are from

(Huang et al, 2012). “The Multi-Mission Bus Demonstration (MBD) is a Johns Hopkins University Applied Physics Laboratory program to demonstrate a government sponsored mission in the standardized 3U (10 x 10 x 30 cm) CubeSat form factor. ... With vicious cost and schedule control, the MBD project is providing a classified DoD payload that will revolutionize the mission area and provide an operationally relevant capability to the war fighter. ... The MBD space vehicles will cater to mission operation versatility and rapid response launch capabilities.”

“MBD is an Advanced Concept Technology Demonstration. To complete the demonstration, two ready-to-launch spacecraft based on non-proven technology had to be designed and developed in less than 10 months and under \$10 million dollars. With little or no COTS parts qualified to meet the mission requirements, new hardware and software development was required. The MBD project is characterized as a super-high-tech project; i.e., new, non-proven concepts requiring extensive development of technologies and system components.”

NASA reliability requirements encourage the reuse of heritage hardware, proven in the past 1,000 satellite development efforts. But the unique CubeSat form factor, at this point, had only 70 Missions. Compatible heritage hardware was not available from the CubeSat COTS community. The MDB mission requirements called for innovative technologies far advanced over anything done previously. “The small volume of a CubeSat platform remains a daunting engineering challenge to overcome. Components were not ‘plug and play,’ requiring, in some cases, vendor collaboration and modification to meet the requirements of the MBD program.”

JHU/APL has more than 70 years’ experience in the design, build, and operation of over 60 spacecraft and 200 instruments, using a tight requirements process and disciplined development to meet NASA space flight requirements. It was evident to the MDB program team that their proven systems engineering procedures would be unable to meet cost and schedule in this highly uncertain technical development effort. They’d have to do something very different to reveal and reduce the uncertainties rapidly and cost effectively.

They did. Their paper, *Agile hardware and software systems engineering for critical military space applications* (Huang et al. 2012), “...discloses the adaptation and application of concepts developed in agile software engineering to hardware product and system development for critical military applications ... created a large paradigm shift from traditional spacecraft development.”

Project uncertainty was rooted in the combination of a small physical envelope constraint, high technical capability requirements, an unprecedented low budget, and an unprecedented short program duration. This was recognized by the MBD sponsor, who was willing to make compromises and accept more risks than the typical NASA mission “in order to balance cost, schedule, and reliability while still meeting all mission requirements. To meet the dramatically constrained volume, costs and schedule while increasing functionality more than ever seen in a CubeSat format, new designs and concepts needed to be created, developed, and manufactured. ... The MBD spacecraft [shown in Figure 5] is designed with all the complex and critical subsystems found within a typical earth observing multi-instrument satellite.”

Taking stock of the project environment, unpredictability and uncertainty appeared high, and a

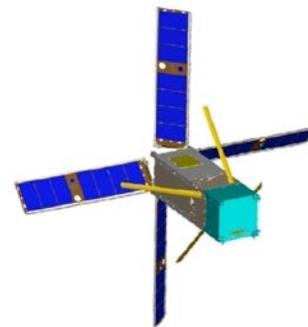


Figure 5 – JHU/APL MBD CubeSat with deployed solar array.

real risk of project success existed. Couched in the CURVE framework outlined in Part 1:

- Capricious: Appetite for stakeholders to stay the course when things look uncoordinated, or when unresolved development issues are allowed to persist. Cultural adjustment of engineers working outside their standard procedures.
- Uncertain: what requirements to use as technical drivers, what technical path to take, how changed subsystem dependencies will interrupt momentum, what untraditional decisions will have to be made, what SME expertise will be needed.
- Risky: it can't be, or doesn't get, done within the constraints.
- Variable: nothing relevant foreseen.
- Evolving: nothing relevant foreseen.

A Scrum-Like Approach to Agile Systems-Engineering

JHU/APL utilized a flat organization structure with six distinct development teams including Payload, Electrical, Software, Mechanical, Ground & Navigation Control, and Avionics. The lead of each development team, called a “Deputy”, reported directly to the MBD Program Manager, called the “Sherriff”. Each development team lead also had direct access to the Customer. The Program Manager reported directly to the head of the JHU/APL Space Department and had the authority to implement any technical or programmatic changes required to ensure the success of the MBD program. Each development team included a small interdisciplinary group of designers and developers, called a “Posse”. While the names for each role are different, the MBD program essentially used Scrum as the basis for the organizational structure, with the Sherriff serving as the Product Owner. Each Posse was essentially a parallel scrum Development Team led by a Deputy, who acted as the team’s Scrum Master.

At the start of each day the MBD team held a “Round-Up” meeting which was attended by everyone on the program. These daily meetings were used to review issues and priorities, and to allow each team to solve problems and react to changes quickly. All of the JHU/APL team leads (Deputies) were collocated in an open office to assure easy and frequent communications between the parallel Development Teams. The MBD program used a traditional Scrum Board to track tasks, issues and assigned priority levels, to identify which team member was responsible for the completion of a task, when that task was scheduled for completion, and the dependencies between tasks.

The emphasis for each Development Team was to deliver working components as early as possible in the development cycle. Rather than hold classic waterfall style life cycle reviews such as a System Requirements Review, Preliminary Design Review, and Critical Design Review, the MBD team held a single comprehensive design review, called the One Design Review, but also held many informal peer reviews with subject matter experts throughout the program life cycle. Whenever possible off-the-shelf components were used. When custom hardware items were required they were designed and manufactured in house using JHU/APL high precision manufacturing facilities. Resource, subsystem, and system level testing was performed using a “build a little, test a little, learn a lot” framework designed to find and resolve issues as early as possible.

Figure 6 shows the system life cycle for the MBD program, which included both iterative and incremental development strategies. During the MBD program several different stages of the

ISO/IEC 15288 life cycle were performed in parallel. For example the Requirements & Concepts, Design & Development, Implementation & Integration, and Test & Evaluation efforts shown in Figure 6 are roughly equivalent to the 15288 Research, Concept, and Development stages. As shown in Figure 6 these four efforts were performed in parallel for a significant portion of the MBD program's life cycle.

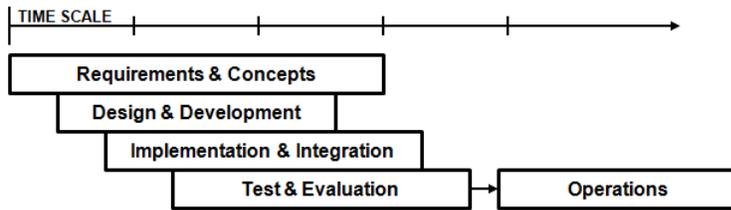


Figure 6. MBD System Life Cycle with Overlapping Stages (Huang, et al. 2012)

According to the MBD development team, using agile system engineering processes was critical to the success of the program. Specifically they said “the process flow used on MBD left the window open to make modifications at a later part of the development. By embracing

uncertainty and carrying open issues forward, changes could be made without dramatically affecting other sub systems. Issues were prioritized and the development team worked to close the items that would force modifications and changes to the system as soon as possible” (Huang, et al. 2012).

The MBD program used sprints with one-day durations, while classic Scrum typically uses sprints one to four weeks in duration. Consequently, Sprint Planning, Daily Scrum, Sprint Review and Sprint Retrospective meetings were combined into a single “Round-Up” meeting at the start of each work day. The MBD Program Manager assumed the role of Product Owner. The program implemented six parallel agile development efforts for the Payload, Electrical, Software, Mechanical, Ground & Navigation Control, and Avionics subsystems of the MBD satellite. Each development team lead performed a role similar to a Scrum Master for their subsystem, but also acted as a Development Team member at the system level. Thus the MBD agile process implementation was similar to a Scrum of Scrums with a sprint length of one day. The need to design, develop and test custom hardware, such as the deployable solar array, required the MBD team to coordinate very short duration software development sprints (1 day) with longer duration hardware development sprints (1 month or more). When custom hardware was required, the MBD team built two prototypes for each hardware element. Each of the hardware prototypes was integrated into the two satellites being built during the program. To the extent possible prototype hardware items were used as production items in the final satellites, even if that required rework such as cutting printed circuit board traces and adding wires to implement a design change.

Agile Architecture and Design Principles

Agile systems and agile systems-engineering processes gain their agility from an architecture and set of design principles that facilitates sustainable adaptability, as discussed in Part1. The MBD program's agile architecture pattern is sufficiently similar to the Scrum Agile Architecture Pattern shown in Figure 4 that little of relevance would be revealed with discussion here. However, the ways in which ten design principles manifest in three categories may be instructive.

Reusable principles include Modularity, Plug Compatibility and Facilitated Reuse. The agile processes used by the MBD program's six subsystem development teams were modular in nature. Once the form, fit and functional requirements were defined for a subsystem the Development Team was asked to deliver incremental capabilities that met those requirements as early as possible in the development schedule. Changes or improvements made to the internal design or

implementation of a subsystem that did not impact the external form, fit or function of the subsystem could be made quickly, with the Development Team lead (Scrum Master) having the authority to make the required design decisions for their subsystem. Well defined and flexible interface standards were defined early on in the program so that individual subsystems could be plug compatible with the other subsystems as well as the spacecraft bus itself. Team members could be and were assigned to different subsystems at different times, provided their skill sets and experience matched the task requirements, employing the Facilitated Reuse principle in this Scrum of Scrums architecture.

Reconfigurable principles include Peer to Peer Interaction, Distributed Control and Information, Deferred Commitment, and Self-Organization. Peer to Peer Interaction was employed in the combination of Daily Roundup meetings attended by each team member as well as the colocation of staff members so that communication among team leads and team members was direct, fast and efficient. Distributed Control and Information was employed in the Daily Roundup meetings, where information was exchanged among all team members. Each team lead had the authority to make design and implementation decisions for their subsystem, while the Program Manager had the authority to make system-wide design and implementation decisions. Decisions at both the subsystem and system levels were made by the staff members who had direct access to the information required to make an informed decision as well as the ability to take immediate steps to implement the decision. The principle of Deferred Commitment was used throughout the MBD program. The MBD engineering team delayed the finalization of designs to allow many new components to be completed and fully tested. Deferring commitment to a specific design allowed modifications to requirements and hardware at a later stage of the development process. Self-Organization was employed within the subsystem teams which were self-organizing in nature. Each team lead had the flexibility to determine which tasks would be accomplished each day, and which team members would be assigned to those tasks. The use of a traditional Scrum Board assisted the self-organization process by allowing team leads and team members to quickly determine if other subsystems were dependent on the timely completion of one of their tasks.

Scalable principles (Dove and LaBarge 2014) include Evolving Infrastructure, Redundancy and Diversity, and Elastic capacity. The systems-engineering process rules and standards were established at the start of the MBD program. Evolving Infrastructure was employed in the Daily Roundup meeting discussions on what was working well and what could work better, and then be quickly implemented by the team leads. Redundancy and Diversity was employed in the use of cross-discipline development teams as well as the use of part time subject matter experts. When required, a member of one team could be assigned to another team to supplement a critical capability in software development, for instance. Subject matter experts could also be brought in to provide critical capabilities that were lacking on a team at any particular point in time, and this capability was facilitated specifically to avoid long term use of expensive subject matter experts beyond their critical need. Elastic capacity was not employed to any meaningful extent as no issues existed that needed this capability: development teams were purposefully kept small so they could quickly react to changes, and only two spacecraft were required.

Discussion

Up to this point this article has principally addressed the practitioner. But there is work yet to do in research, and a few words might provide direction for some of what is still needed.

Part 1 and Part 2 of this article provide *some* framework and foundational considerations for

developing an agile systems-engineering life cycle model. Synergistic guidance from the work of others needs to be considered as well, particularly in the opportunity to address how agile systems engineering concepts might help in contracted development at fixed price and specification. Three bodies of thought emerging in the eighties offer some key perspectives that may have had more influence on what has happened since in various agility perspectives than is explicitly recognized, and in any event merit re-evaluation against today's understandings and objectives.

The first perspective came in 1981 with the publishing of *Systems Thinking, Systems Practice*, (Checkland 1981), questioning the application of rigid systems engineering practices to a class of systems that don't appear amenable to logical thinking, yet they are pervasive in the systems around us that have multiple stakeholders in various evolving states of satisficing for the moment. Checkland went beyond questioning, offering an alternative approach now known as soft systems methodology.

The second (chronologically) perspective came in a 1986 Harvard Business Review paper, *The New New Product Development Game* (Takeuchi and Nonaka 1986), acknowledged in (Sutherland and Schwaber 2007: 6) as sparking the thoughts that led to Scrum. That paper profiled a general process that engineered breakthrough innovative products composed more of hardware than of software, and exposed the role of what they called "subtle management", which affected product outcome by working behind the scenes to constantly rebalance diversity within the development teams. This concept is ignored by Scrum, yet crucial to the success of a rapid agile learning process.

The third perspective came in 1988 with the publication of *A Spiral Model for Software Development and Enhancement* (Boehm 1988). This marked a new turn of thought, offering an iterative, incremental alternative to the sequential waterfall approach, subsequently refined in a fundamental view (Boehm 2000).

Oversimplifying, Checkland put a focus on people, Takeuchi and Nanoka put a focus on product, and Boehm put a focus on process. All were concerned with uncertain and unpredictable engineering efforts. Each of these developments in the '80s gave legitimacy to, and spurred interest in, questioning the old ways and exploring new paths; paths meant to deal with uncertain and unpredictable operational environments.

The '90s might be viewed as a period of gestation, experimentation, research, and discovery.

It is suggested here that at the turn of the millennium three more bodies of synergistic relevant thought emerged. The first perspective came early in 2001 with the publishing of "*Response Ability – the Language, Structure, and Culture of the Agile Enterprise*" (Dove 2001); which organized the agile systems research findings of the '90s into domain-independent enabling fundamentals for agility in engineered systems of any kind. The second perspective came later that same year with the publication of *Agile Software Development with Scrum* (Sutherland and Beedle); detailing a systems engineering management process for agile software development, and reviewed in this article for its agile enabling core. The third perspective came in 2002 published as *Agile Software Development Ecosystems* (Highsmith 2002); notable for its sane and revealing coverage of the principle software development practices sharing the agile family name at that time.

The six references suggested were ordered by their first appearance, and included because of the line of thinking they initiated. There is no pretention that they encompass all of the thought that needs consideration for developing an agile systems-engineering life cycle model, nor suggestion that seminal new thinking won't continue to emerge.

It is time to develop an agile systems-engineering life cycle model. This model, if a single one is sufficient, must take into account at least three different types of systems engineering, articulated well in (Sheard 2000): Discovery (very high complexity in problem space), Programmatic (complexity in solution space and possibly organizational), and Approach (complexity in the variation of applications, and possibly product lines).

An agile systems-engineering life cycle model might start with the framework displayed in Figure 2, and be guided by (ISO/IEC TR 24748-1 2010) toward identifying fundamental principle-based activities and processes that provide agility, independently as well as collectively, across all stages that warrant an agile approach. This model might justify the application of these principles, activities, and processes by identifying common systems-engineering environmental situations in need of agile response capability. Ideally, the model would be supported with case studies in a variety of systems engineering domains.

Conclusion

Unique to this article is the suggestion of a parallel between Peter Checkland's Soft Systems Methodology and the situation faced when an agile systems-engineering process is appropriate; the introduction of a ISO/IEC 15288 compatible life cycle framework for agile systems-engineering; an examination of the source of agility in the popular process known as Scrum; an examination of JHU/APL's CubeSat agile systems-engineering process for developing hardware/software systems, albeit an engineering project with more latitude than fixed price and requirements projects; and finally; a foundation for next steps toward developing a timely domain-independent agile systems-engineering life cycle model.

The growing acceptance and adaptation of agile software development methods has passed the tipping point in the software world, and is now motivating expectations in broader domain-independent systems engineering. The popularity of Scrum as a project management process, and the Siren song of the Manifesto for Agile Software Development, has created for some an expectation of a clear path to broader application. On the opposite extreme are those who make a clear case for inapplicability, e.g., (Carson 2012). Neither camp is actually focused on agility, but rather on specific software development management practices and principles that share *agility* as a family name.

There is no reason to expect domain specific software development practices to be applicable in domain independent systems engineering. For a simple disconnect example, (Carson 2012) observes that in software development the code designer is also the code fabricator; whereas in hardware, the designer's product is an intermediate document that is intended to drive the separate activities of a fabricator with a different world view. Integrated product teams attempt to address some of the communication issues, but inherently hardware design effort and fabrication effort are sequential activities of different time durations and different costs – at least currently in this very early period of automated 3D fabrication capability.

The ball is in motion toward the goal of an agile systems-engineering discipline. Perhaps many different balls are in motion, as the pressure to do systems engineering under accelerating environmental dynamics isn't waiting for a common disciplined understanding. We should, as practitioners and as researchers, identify and define design and operational guidance for adaptive system engineering processes.

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Biography

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