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Evolvability-Related Options in Military Systems of Systems

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Abstract

This paper presents results of case investigations of evolvable systems of systems (SoS) in the military domain. The selected SoS cases illustrate examples of specific options implemented by architects in designing SoS that resulted in evolvable SoS. The research aims to further validate the usefulness of design principles for architecting systems that possess desirable lifecycle properties such as evolvability, and contribute real-world examples that architects may use to inspire specific design options for their system of interest.

Keywords: Evolvability; Design Principle; Change Option; Path Enabler; Change Mechanism; System of Systems.

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1. Introduction

The concept phase of system design requires systems architects to think beyond the static functional requirements. The rapid pace of change in operational environments, and respective change in stakeholder needs, drive the need for architects to consider lifecycle properties of systems (i.e., “ilities”). Designing for ilities enables systems architects to avoid architecture alternatives that are well-suited to present needs, yet unable to sustain value delivery over the lifespan of the SoS. This paper presents results of case investigations of evolvable systems of systems (SoS) in the military domain. The selected SoS cases illustrate examples of specific options implemented by architects in designing SoS that resulted in *evolvable* SoS. The research aims to further validate the usefulness of design principles for architecting systems that possess desirable lifecycle properties such as evolvability, and contribute real-world examples that architects may use to inspire specific design options for their system of interest.

1.1. Motivation

Designing systems (and SoS) that are evolvable is motivated by the dynamic and interconnected world in which they operate. The system environment is in continuous evolution, and a system may need to operate in contexts for which it was not originally intended[1]. Changing contexts may result in the system failing to deliver value to its stakeholders. Such changes can also lead to shifts in the perception stakeholders have of the system (e.g., improvements in technology led to the advent of smartphones, which now overshadow the use of traditional cell phones). It is in such an uncertain operational environment that the ability of a system to evolve so to respond to negative (or positive) consequences of exogenous changes becomes crucial. This paper first presents a framework for the analysis of evolvability in empirical examples, which relies on two main constructs: design principles for evolvability and change options. Then, such a framework is used to describe the ways in which evolvability has been instilled and used in some past and current military SoS.

1.2. Evolvability

The concept of evolvability has long been explored in the field of biology, where it has been defined as “the ability of a population to both generate and use genetic variation to respond to natural selection”[2]. In the field of systems engineering, analogies between artificial systems and biological organisms have been drawn, and the concept of biological evolvability has often inspired the concept of systems evolvability. For example, Sussman (2007) describes evolvable systems as being able to accommodate adaptive variations in some locales without changing the behaviour of subsystems in other locales[3]. In the field of SoS engineering, evolvability has been defined as the “ability of the architecture to handle future upgrades”[4], with specific references to how an evolvable SoS is architected with an eye for technologies and features that are required to support possible future capabilities. Finally, in an attempt to define evolvability broadly enough so that it would be unambiguously applicable to different domains, Beesemyer (2012) proposes the following definition for evolvability: “the ability of an architecture to be inherited and changed across generations [over time].”[5] This definition is the culmination of a larger collaborative research effort aimed at the development of methods to design for evolvability[6]. In their work, Beesemyer and Fulcoly collect different concepts and ideas regarding evolvability from various fields (from biology, to technology innovation, to systems engineering) and synthesize them in a set of design principles for evolvability, listed in §3. Beesemyer’s definition of evolvability rests upon a key distinction among systems’ architecture, design and instance – where the architecture is the highest level of abstraction among the three[5]. While changeability can take place at all three levels of abstraction, evolvability is only linked to architecture changes, and can be thought of as “architecture-level changeability.”

2. Military Systems of Systems

The evolvability study looked at various SoS – all conceived for military purposes. Three of these were selected for discussion in this paper, spanning three unique SoS domains: mission, platform and IT[7]. The mission SoS chosen is the Ballistic Missile Defense System (BMDS); the platform SoS is the Army Brigade Combat Team (BCT)

Modernization program; and the IT SoS is the Defense Information Systems Agency (DISA) Joint Information Enterprise (JIE), specifically Mobile Solutions. All three of these SoS are very large in scope, and benefit from large budgets to consider new or different SoS implementations[8]. The possibility of considering different SoS evolution increments is vital in order to sustain value delivery in fast-changing operational environments (e.g., US Quadrennial Review may disrupt the budgets and scopes of the above-listed SoS, which must be able to continue to deliver value).

The Ballistic Missile Defense System (BMDS) is a mission SoS composed of several constituent systems and supporting efforts. Its main goal is to enable a robust, layered defense against hostile missiles in all phases of flight – boost, intermediate, and terminal. United States ballistic missile defense efforts can be traced to the World War II years, in an attempt to respond to the German V-2 missile, which was a threat for US' European allies[9]. Initially, it turned out to be an arduous endeavor, and in fact it wasn't until 1960 that a US guided missile test resulted in a success. Through the years, the program has received different names and alternate attention, experiencing low peaks during the years of the Antiballistic Missile Treaty (1972-2002). The current version of the BMDS was deployed in 2004 with limited interception and detection capabilities, which have been increased since that time. The BMDS SoS architecture includes: networked sensors (including space-based) as well as ground-based and sea-based radars for target detection and tracking; ground-based and sea-based interceptor missiles for destroying a ballistic missile using either direct collision ("hit-to-kill") technology, or an explosive warhead; command, control, battle management, and communications network providing the operational commanders with the needed links between the sensors and interceptor missiles.

The Brigade Combat Team (BCT) Modernization Program[10] was announced in 2009 to replace the Future Combat System (FCS) program, which had been in effect since 2003. It is a platform SoS formulated using the lessons learned from FCS and its focus is on responding quickly to evolving war fighter needs in a rapidly changing security environment. The SoS leverages much of the knowledge and technologies developed under the FCS program, which was cancelled due to cost and schedule overruns.

The Defense Information Systems Agency (DISA) is an agency within the Department of Defense that provides information technology and communication support to all entities contributing to the defense of the United States – from the president, to military services, to soldiers. The mission of DISA is to "provide, operate, and assure command and control, information sharing capabilities, and a globally accessible enterprise information infrastructure in direct support to joint Warfighters, National level leaders, and other mission and coalition partners across the full spectrum of operations."[11]

3. Framework for Evolvability Analysis

The evolutionary changes these SoS have undergone (or are undergoing) have been examined through the lenses of two constructs: design principles and change options. For every evolution increment observed to have occurred, an investigation determined what change options appear to be involved, as well as what design principles may have inspired the respective options.

3.1. Evolvability Design Principles

Wasson (2006) defines design principles as "guiding thoughts [for design] based on empirical deduction of observed behaviour or practices that prove to be true under most conditions over time."[12] In practice, design principles serve to help intentionally create desirable properties in a system (e.g., survivability, evolvability, flexibility, etc.). In the context of this research, design principles are linked to the inclusion of change options in the initial design (or redesign) of the SoS.

There is a growing literature for the use of design principles in the architecting of systems. For example, in the case of survivability, Richards (2009)[13], Jackson (2012)[14], and Mekdeci[15] (among others) have contributed to an extended list of design principles. As mentioned in §1.2, evolvability design principles have been derived from various domains (biology, technology innovation, systems engineering). The set of design principles used in this study are the result of recent research at MIT[5,6,16]. This set, listed in Table 1, consists of a synthesis of evolvability design principles inspired from various disciplines, relevant to systems engineering.

Table 1: Evolvability design principles.

Design Principle	Description
Leverage Ancestry	Employing successful design choices of assets, capabilities and/or operations from all prior generations of the system
Disruptive Architectural Overhaul	Re-architecting significant portions of the existing system or program at the same time in order to reduce the negative impact that making many smaller changes would have
Mimicry	Imitating or duplicating successful design choices of assets, capabilities and/or operations from other systems/domains for a similar purpose
Resourceful Exaptation	Repurposing assets or design choices from prior generations or other systems/domain in order to provide capabilities for which they were not originally selected
Decentralization	Distributing assets, capabilities and/or operations to appropriate multiple locations, rather than having them located in a single location
Targeted Modularity	Isolating parts of the system to reduce interdependencies in order to limit undesirable effects caused by either uncertainties or intentional changes
Integrability	Designing interfaces for compatibility and commonality to enable effective and efficient integration of upgraded/new system components and constituents
Reconfigurability	Creating intentional similarities in form and/or function of various system assets, capabilities, and/or operations to facilitate reuse or reallocation
Redundancy	Intentional duplication of selected assets, capabilities and/or operations to enable their future redistribution without compromising existing requirements
Scalability	Making design choices that allow scaling of resources and/or assets up or down in order to accommodate uncertainties and emergent needs
Margin	Architecting for intentional excess capacity in specific capabilities and/or operations to meet emergent needs without compromising existing requirements (i.e. meet or exceed future requirements)
Slack	Intentionally under-allocating or over-allocating specific available assets and/or resources in order to reserve excess capacity for accommodating uncertainties (i.e. prevent violation of constraints)

The first four in the set – leverage ancestry, disruptive architectural overhaul, mimicry, and resourceful exaptation – can be thought of as *strategies* design principles. Such design principles are not directly related to the architecture of the SoS, but rather suggest strategies for facilitating the achievement of evolvability properties. The remaining design principles in this set are *structural*, as they can influence the architecture of the SoS directly (e.g., a modular design implies a different architectural structure than a monolithic one).

3.2. Change Options

A change option is the ability to exercise an action or decision (e.g., swap payload on UAV) that will change the current state of a system – in many cases in order to respond to variations in the environment or stakeholder needs[17]. The option itself is only possible because of the union of two distinct concepts: *path enabler* and *change mechanism*. The change mechanism is the *method* through which a system goes from state A to state B (e.g., swapping payload on UAV); the path enabler (i.e., physical object, action or decision) is *what* gives the "option" of executing the change mechanism (e.g., modular payload bay in original design).

3.3. Descriptive Framework

The descriptive framework used for capturing identified evolvability-related options is shown in Fig. 1. In this diagram, design principles are depicted as what underlies (inspires) the insertion of a change option in the SoS. The execution of change options is then related to an evolution increment. Two primary types of options for every evolution event (i.e. transition from architecture A to architecture B) were investigated: those that have been used to implement the evolution, and those that were introduced into the SoS by the evolution (if any) – and that can potentially enable future evolution increments of the architecture.

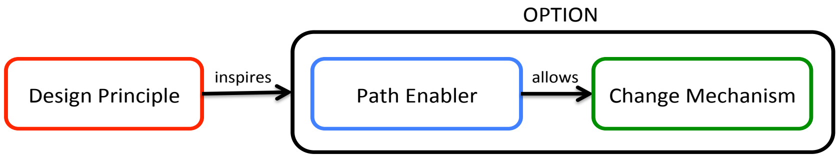

Fig. 1. Framework for the analysis of how evolvability has been instilled in the SoS.

4. Evolvability-related Options

In this section, a selected number of evolvability-related options found during the investigation of the military SoS are presented. For each SoS domain type – mission, platform or IT – one or two evolution increments are presented. Each of these may have one or more associated options.

4.1. Mission SoS – BMDS

The first evolution increment considered is the inclusion of the Terminal High Altitude Area Defense (THAAD) interceptor battery in the BMDS in 2008. The BMDS program was officially launched in 2004, with the deployment of five long-range Ground-based Midcourse Defense (GMD) interceptors at Fort Greely, Alaska. At that point in time, the operational capabilities of the SoS were limited. In terms of intercepting capabilities, the SoS featured GMD interceptors, accompanied by the deployment of PAC-3 interceptors for short-range defense and the Aegis SM-3 interceptors for medium-range defense of the terminal segment (near US territory). In 2008, the first THAAD (Terminal High Altitude Area Defense) interceptor battery (land-based) was added to the BMDS. This new interceptor provided the BMDS with additional capability to intercept and destroy ballistic missiles inside or outside the atmosphere during their terminal phase of flight. One of the key enablers for the inclusion of this constituent system was the Command and Control Battle Management System (C2BMC), which provided the communication and data-management backbone for easily *integrating* THAAD within the current command and control nodes of the SoS.

In this evolution increment, the C2BMC system is the key path enabler that allowed for the "including new interceptor" change mechanism, as shown in Fig. 2. Behind the design of the C2BMC is the design principle of *integrability*. This system in fact includes many technical features that ensure an easy and secure integration of new constituent systems in the BMDS. For instance, Tactical Datalink 16, a military data exchange network also used by NATO, allows for exchange of tactical pictures in near real time, as well as text messages and voice messages. It is an important tool for ensuring interoperability and it is critical for a layered defense. In addition to Datalink 16, Extremely High Frequency (EHF) satellite communications is a key element that enables the creation of an integrated network, thereby facilitating successful engagements via timely and accurate data sharing. Global Engagement Manager (GEM) allows for the integration and coordination of information, ready to be used by decision makers. It can calculate a common threat track from multiple sensors through data fusion, with sufficient data accuracy and timeliness for successful engagement. Finally, multiple and diverse paths in the Communication Network combat sensor outage or jamming, while encryption devices, routers and switches (each with specific access control lists – ACLs) further protect the internal systems and allow only identified and approved users and systems to access the C2BMC data.

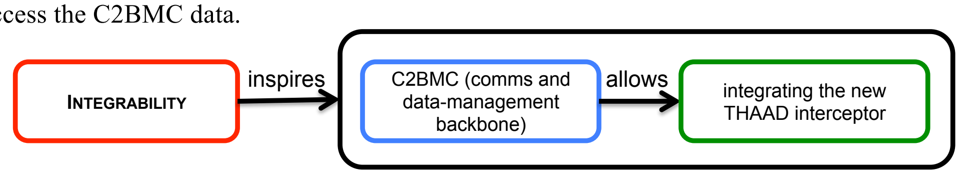

Fig. 2. Change option for the inclusion of THAAD system is linked to design principle of integrability.

The second evolution increment of the BMDS discussed here is the Phase Adaptive Approach (PAA) initiative, announced by President Obama in 2009[18]. PAA was conceived to enable the BMDS to extend its capabilities in European territory in order to deal with the threats posed by Iranian short-range and medium-range ballistic missiles to U.S. assets, personnel and allies. The first deployment of a ballistic missile defense asset in Europe was in March 2011, when the USS Monterey ship was placed in the Mediterranean Sea. This ship is a guided-missile cruiser of the Ticonderoga class, equipped with a sophisticated Aegis radar system designed to detect ballistic missiles. In terms of detection and tracking, the SoS used sea-based sensors mounted on the ship, as well as a forward-based X-band radar on European land (the first EPA radar was deployed in Turkey in late 2011). This strategy resonates with the design principle of *decentralization*: the presence of highly mobile Aegis BMD ships and other globally transportable systems (such as X-band Radar or THAAD) allowed for reallocating capabilities (intercepting, tracking, etc.) and resources to European bases. This flow is shown in Fig. 3.

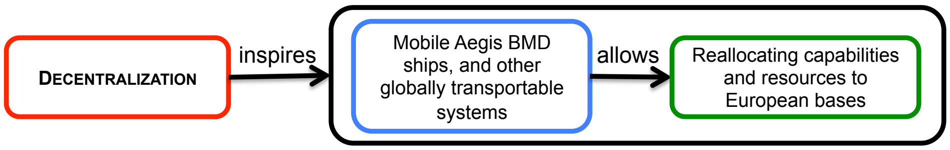

Fig. 3. Change option for PAA evolution increment linked to the design principle of decentralization.

The PAA, as agreed upon by the U.S. and its allies, is a phased approach characterized by more than one increment. Although possible to deploy assets across various geographic locations in Europe from the start, it was decided to allow for some *slack* by fielding ships solely in the Mediterranean Sea during the first phase of the approach. By agreement, though, the U.S. would be able to deploy more assets "ashore" in the European countries of Romania and Poland (as it is currently planned to happen by 2018)[18]. This potential option is depicted in Fig. 4, and, when (and if) executed, it will enable another significant evolution increment for the SoS.

Fig. 4. An example of instantiation of the design principle of slack for the PAA case.

4.2. Platform SoS – BCT

As mentioned in §2, The Brigade Combat Team (BCT) Modernization Program was announced in 2009 to replace the FCS program that had been in place since 2003. It was intended to be a response to the failures that the FCS had undergone. The main objective of the BCT SoS is to respond quickly to changing warfighter needs in a rapidly evolving security environment. The SoS leadership team has tried to leverage knowledge and technologies developed under the FCS program as much as possible. After some lessons learned, they planned to change the decisional structure regarding Army capability upgrades. Instead of making one modernization decision and applying it for long periods like in the FCS program, the BCT Modernization Program performs upgrades to the Army incrementally through capability packages. Each capability package can be thought of as a module, which can enable faster upgrades of single packages, as well as upgrades of some selected packages in parallel. By intentionally modularizing the structure of the program, interdependencies are reduced, and it is now simpler to implement an evolution increment. Hence, this new approach allows for rapid incremental upgrades implementation for defense capabilities, which in turn enables the Army to respond more quickly to warfighter needs. The option behind this evolution increment is illustrated in Fig. 5.

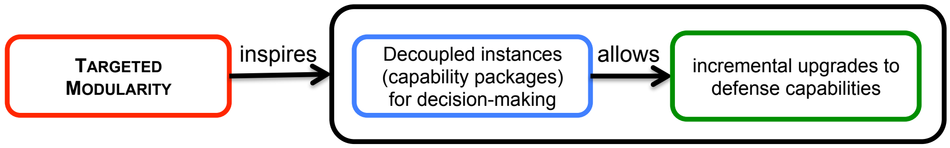

Fig. 5. Isolated capability packages allow for incremental upgrades to defense capabilities. This option is linked to the evolvability design principle of targeted modularity.

4.3. IT SoS – DISA JIE Mobile Solutions

Defense Information Systems Agency (DISA) is evolving the current information environment to enterprise-level secure classified and protected unclassified mobile solutions, through a subscription-based service in Fiscal 2014. The agency is putting forth the Joint Information Environment (JIE), a central information sharing solution to improve DoD's ability to share information, not just between the services, but also with its industry partners and other government agencies. Due to the fact that there are so many separate networks, information sharing isn't as efficient as it could be. JIE is designed to take the separate networks and collect these into a shared architecture, to be fully realized between 2016 and 2020. The research has focused specifically on Mobile Solutions.

In fiscal 2014, DISA will begin offering mobile services as a subscription-based service, taking advantage of commercial-carrier infrastructure and providing entry points for classified services. Mobility at the enterprise level is being architected from the start, with consideration of joint information environments and providing efficiencies early on to create interoperability. The overall goal is to ensure that mobile devices, apps, email and other functions, and wireless networks that support them can operate securely regardless of the environment, and can adapt to rapidly changing technology and scale to accommodate increasing numbers of users. In order to achieve this goal, it is important that new devices are easily integrated into the network, which is why SoS architects designed system interfaces for commonality and compatibility, allowing a wide variety of current and future devices to be added as the SoS evolves. These decisions embody the design principle of *integrability*, leveraging commonality and compatibility to allow a diversity of devices to be integrated into the system, even as technology changes and new devices emerge.

Furthermore, the design principle of *decentralization* can be associated to the choice of two components: the Mobile Device Management (MDM) system and the Mobile Application Store (MAS). The MDM provides for decentralized capability for policy enforcement and permissions, by distributing this capability at multiple DISA enterprise computing centers rather than a single center. The MAS, operating with MDM, can deliver, update, and delete applications on mobile devices without the end user returning the device to a centralized location for service. This means every user is able to individually evolve their device as needed.

Finally, the design principle of *scalability* was also used in the DISA JIE Mobile Solution evolution increment. The mobility services used – both unclassified and classified – are scalable to accommodate increasing (or decreasing) numbers of users. The SoS architecture uses commercial carriers for providing subscription-based services. Commercial carriers and other unclassified access networks provide controlled connectivity between users and mobile enterprise. Subscription-based services are scalable, both up and down as needs change. As such they represent a path enabler in the change option illustrated in Fig. 6. Operational capability is expected to grow with subscription-based services up to 100,000 devices – starting from 1,500 initial devices.

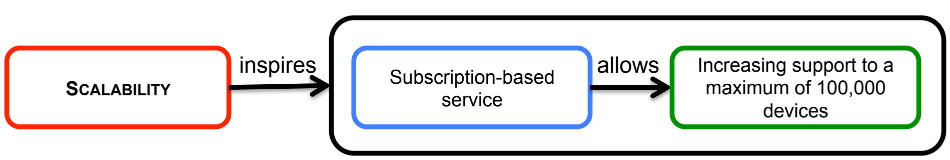

Fig. 6. Scalability-inspired change option for future evolution increments of DISA JIE Mobile Solutions program.

5. Discussion

The research presented in this paper is part of a larger ongoing project, in which a variety of military SoS have been investigated, more than a dozen evolution increments observed, and nearly fifty options identified. The objectives of the larger research project are to examine past and current SoS that have demonstrated evolvability properties, in order to validate the usefulness of the design principles listed in Table 1. Furthermore, the research will yield a set of empirical evolvability examples that may be of use to architects to inspire particular options.

Although the research effort is still in its early stage, some preliminary patterns are starting to form. Thus far, every design principle was encountered across all SoS types and evolution increments considered. However, some design principles appear to be less frequent than others. The long-term goal is to have enough data points to be able to discern differences in use of design principles across these and more dimensions. It is also important to note that the three SoS types discussed (mission, platform and IT) are not collectively exhaustive in the defense systems domain. However, they are mutually exclusive, and provide strong evidence of the usefulness of evolvability design principles for different SoS types. Future work will expand the current set to approach collective exhaustiveness.

This paper has shared preliminary findings for evolvability of military SoS. Continued research will generate additional case examples and further validation of the evolvability design principles. Ongoing research is also looking at SoS evolvability with respect to what is specifically evolving: evidence is being gathered that shows the SoS evolvability may be linked to the SoS program (e.g., FCS evolving to BCT Modernization), the SoS architecture as a whole, or to a constituent system that impacts the evolvability of the SoS as a whole.

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