Global Positioning System II

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This article highlights some of the differences between the so-called classical, traditional, or conventional systems engineering (SE) approaches and the newer, and, as yet, less defined principles of system of systems (SoS) engineering (SoSE), enterprise systems engineering (ESE), and/or complex systems engineering (CSE) or complex adaptive systems engineering (Gorod et al. 2015). The topic is still somewhat controversial, especially considering those that are skeptical that broader views of SE might work better when one is immersed in trying to cope with our most difficult problems. Indeed, the lack of a unified theory of SE is one of the prime motivations for producing and analyzing case studies to develop more knowledge of what seems to work, what does not seem to work, and reasons why, really challenging SE environments.

For addition information, refer to Systems Engineering: Historic and Future Challenges, Systems Engineering and Other Disciplines, Enterprise Systems Engineering, and System of Systems Engineering.

Rather than modifying the previous discussion of the Global Positioning System Case Study in SEBoK, the focus is on comparing and contrasting the older and newer forms of SE by commenting on quotations from the original case study source documents (O'Brien and Griffin 2007).

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Contents

Preface

The original case study begins by describing systems engineering (SE) principles. For example,

> System requirements are critical to all facets of successful system program development. First, **system development must proceed from a well-developed set of requirements**. Second, regardless of the evolutionary acquisition approach, the **system requirements must flow down to all subsystems and lower-level components**. And third, the **system requirements must be stable, balanced, and must properly reflect all activities in all intended environments**. However, system requirements are not unchangeable. As the system design proceeds, if a requirement or set of requirements is proving excessively expensive to satisfy, the process must rebalance schedule, costs, and performance by changing or modifying the requirements or set of requirements. (O'Brien and Griffin 2007, p. 9)

The Global Positioning System (GPS), including its multi-various applications, was developed over many years as the result of the efforts of a host of contributors. It is very difficult to believe that the classical, traditional or conventional systems engineering approach described in the above paragraph (especially those phrases highlighted in bold by the present authors) was truly

responsible for this remarkable achievement that so profoundly impacts our lives. Rather, some more advanced form of systems engineering (SE), that might be called system of systems (SoS) engineering (SoSE), enterprise systems engineering (ESE), or complex (adaptive) systems engineering (CSE), or a blend and/or combination of these approaches or methodologies, had to be responsible. This premise is supported explicitly and repeatedly in the following case study revision using bold font.

Continuing, the following quoted paragraphs seem flawed in several places highlighted in bold. The bold phrases might be replaced by the phrases in brackets [...]. Such brackets might also include other editorial comments of the present authors.

> Systems engineering includes making key system and design trades early in the process to establish the system architecture. '''"These architectural artifacts"''' [This architecture] can depict any new system, legacy system, modifications thereto, introduction of new technologies, and overall system-level behavior and performance. Modeling and simulation are generally employed to organize and assess architectural system alternatives at this stage. System and subsystem design follows the functional [system] architecture [as defined from a functional point of view]. System architectures designs are modified if elements are too risky, expensive, or time-consuming. (O'Brien and Griffin 2007, p. 9)

A good architecture, once established, should guide systems development, and not change very much, if at all, at least compared to possible changes in the system design, which, of course, can evolve as one learns more about the problem and potential solutions that may increase the system's capability. Thus, it is crucial to not confuse architecture with designs instantiating the architecture, contrary to what seems to be the case in (Ricci, et al. 2013).

> Important to the efficient decomposition and creation of functional and physical architectural designs are the management of interfaces and the integration of

subsystems. Interface management and integration is applied to subsystems within a system or across a large, complex system of systems. Once a solution is planned, analyzed, designed, and constructed, validation and verification take place to ensure satisfaction of requirements. Definition of test criteria, measures of effectiveness (MOEs), and measures of performance (MOPs) are established as part of the requirements process, taking place well before any component/subsystem assembly design and construction occurs. (O'Brien and Griffin 2007, p. 10)

In the quoted paragraph just above, bold phrases note the emphasis on a reductionist approach, reductionism, where great attention is paid to the subsystems and managing the interfaces among them. This is the antithesis of a holistic approach where one concentrates on the whole system, recognizing that it is difficult to identify overall system behavior as depending on any particular subsystem or set of subsystems. In a truly complex system that is continually evolving, the above-mentioned requirements process is flawed because the system is continually changing, i.e., the system is evolutionary; the requirements are either ill-defined at the outset, or are modified because stakeholderschange their minds, or become somewhat irrelevant because the system environment changes.

There are several excellent representations of the [usual traditional or conventional] systems engineering process presented in the literature. These depictions present the current state of the art in maturity and evaluation of the systems engineering process. One can find systems engineering process definitions, guides, and handbooks from the International Council on Systems Engineering (INCOSE), European Industrial Association (EIA), Institute of Electrical and Electronics Engineers (IEEE), and various Department of Defense (DoD) agencies and organizations. They show the process as it should be applied [Really? In all situations?] by today's experienced practitioner. One of these

> processes, long used by the Defense Acquisition University (DAU), is [a model] not accomplished in a single pass. This iterative and nested process gets repeated to the lowest level of definition of the design and its interfaces. (O'Brien and Griffin 2007, p. 10)

The above description appears to be written with pride without any acknowledgement that this SE methodology might fail to work if applied according to these guidelines, or that there might be new SE techniques that could be more effective in some situations. Again, this reflects a reductionist approach that ignores holism and emergent properties that might not be explained even when thoroughly understanding the systems components and their interactions. On the positive side, the next paragraph suggests how the world is changing and hints that something more is needed. Nevertheless, the advice seems to be oriented toward applying the existing SE discipline more vigorously instead of seeking new methods that might be more effective.

> The DAU model, like all others, has been documented in the last two decades, and has expanded and developed to reflect a changing environment. Systems are becoming increasingly complex internally and more interconnected externally. The process used to develop aircraft and systems of the past was effective at the time. It served the needs of the practitioners and resulted in many successful systems in our inventory. Notwithstanding, the cost and schedule performance of the past programs are replete with examples of well-managed programs and ones with less-stellar execution. As the nation entered the 1980s and 1990s, large DoD and commercial acquisitions experienced overrunning costs and slipping schedules. The aerospace industry and its organizations were becoming larger and were more geographically and culturally distributed. Large aerospace companies have worked diligently to establish common systems engineering practices across their enterprises. However, because of the mega-trend of teaming in large (and some

> small) programs, these common practices must be understood and used beyond the enterprise and to multiple corporations. It is essential that the systems engineering process govern integration, balance, allocation, and verification, and be useful to the entire program team down to the design and interface level. (O'Brien and Griffin 2007, p. 11)

Finally, in the next paragraph, there is a suggestion that SE could be made more sophisticated but there is no mention of addressing people problems or advocating a broader transdisciplinary approach.

> Today, many factors overshadow new acquisition; including system-of-systems (SoS) con- text, network centric warfare and operations, and rapid growth in information technology. These factors are driving a more sophisticated systems engineering process with more complex and capable features, along with new tools and procedures. One area of increased focus of the systems engineering process is the informational systems architectural definitions used during system analysis. This process, described in DoD Architectural Framework (DoDAF), emphasizes greater reliance on reusable architectural views describing the system context and concept of operations, interoperability, information and data flows, and network service-oriented characteristics. (O'Brien and Griffin 2007, p. 11)

The last two sections of the systems engineering principles portion of the original case study address case studies themselves, mainly for academic purposes, to help people appreciate systems engineering principles, and the framework used in the case study, namely the rather narrowly defined Friedman-Sage framework that will be discussed briefly in Section II below.

The treatment of the reason for case studies is quite good in that it talks about the benefits of applying systems engineering principles, as highlighted from real-world examples of what works and what does not. Except near the end, where there is allusion to the

possibility of new endeavor systems engineering principles, the principles espoused tend to be traditional or conventional.

On the other hand, based upon the original case study (O'Brien and Griffin 2007), if one views the boundary of the GPS system to include primarily the technology associated with the GPS space segment and its controlling ground network, then it can be assumed that system was likely implemented primarily by following traditional or conventional systems engineering processes. If one takes this viewpoint, then all of the above criticism which attempts to point out some of the shortcomings of conventional systems engineering, may seem vacuous at best, or politically incorrect at worst. It may well be that many would rather not denigrate the original GPS case study by exposing it to the possibilities of a broader system engineering approach.

Unless otherwise indicated, as the present authors have already been doing, unchanged quotations from the existing SEBoK are indented below. Modifications to such quotations are shown in brackets [...]; deletions are not necessarily shown explicitly.

Background

> The Global Positioning System (GPS) case study was developed by the United States Air Force Center for Systems Engineering (AF CSE) located at the Air Force Institute of Technology (AFIT). The GPS is a space-based radio-positioning system. A constellation of twenty-four satellites, including three spares, comprise the overall system which provides navigation and timing information to military and civilian users worldwide. GPS satellites, in one of six Earth orbits, circle the globe every twelve hours, emitting continuous navigation signals on two different L-band frequencies. The system consists of two other major segments: a world-wide satellite control network, and the GPS user equipment that can either be carried by a human user or integrated into host platforms such as ships, vehicles, or aircraft.

A user needs to receive signals from at least four GPS

satellites simultaneously (satellite orbital positions and terrestrial terrain blockage can be issues that degrade performance) to determine one's position in three dimensions; the altitude determination is typically less accurate than the other two dimensions.

When looking at [GPS], it would be difficult to imagine another system that relies so heavily upon such a wide range of [domains containing systems that must interact effectively to achieve successful GPS operation]. It is evident that [GPS directly relates to many domains and applications including:

- position location and tracking
- time synchronization
- navigation
- transportation
- times of arrival
- air traffic management
- situational awareness
- jam-resistant communications
- business and commerce
- farming
- aerospace
- sensing nuclear detonations from space
- military war-fighting
- targeting
- weapons delivery
- etc.].

[GPS is] an example of [a collaborative (Dahmann, et al. 2008) systems of systems (SoS)]. As such, no one is in charge, and the capabilities (not requirements) flow from the bottom-up, as opposed to top-down.

Purpose

The GPS case study includes a detailed discussion of the development of the GPS and its components, as well as other

applicable areas. The reader of this study will gain an increased understanding of the effect that GPS has on military and commercial industries in the context of the systems engineering support required to achieve success.

This may be, but the principal purpose of this revised case study is to suggest a broader view of GPS that discusses signature aspects of SoS, enterprises, and complex systems, and emphasizes SoSE, ESE, and CSE.

[AF CSE] was tasked to develop case studies focusing on the application of [SE] principles within various aerospace programs. The GPS case study [was developed in support of SE] graduate school instruction using the Friedman-Sage framework (Friedman and Sage 2003) (Friedman and Sage 2004).]

However, the Friedman-Sage framework involves only two contractual stakeholders, the Government and the contractor; further, the framework is limited to the traditional or conventional SE life cycle which mainly treats activities in a linear instead of nonlinear fashion; still further, only risks are considered, not a balance of risk and opportunity. Thus, the present authors believe a broader framework embracing SoSE, ESE, and CSE is more appropriate.

Challenges

In the original case study, the first highly technical section (Section 2) was the system description. The original idea derived from trying to determine the precise orbital parameters of the first artificial satellites, such as Sputnik, launched by the Soviets in 1957. Researchers at Johns Hopkins realized the inverse, that if one knew precisely the orbital parameters, the locations of ground stations receiving satellite signals could be determined quite accurately. (O'Brien and Griffin 2007, p. 20.)

GPS got its start in the early 70s (O'Brien and Griffin 2007, p. 19), building upon several previous satellite navigation systems. The primary motive was very accurate position information for the purposes of military applications. For example, the U.S. Air Force

wanted to deliver nuclear weapons from bombers with unprecedented accuracy and precision. (O'Brien and Griffin 2007, p. 29)

With such an intense interest from the military, the first real challenge, other than the many technical challenges of making GPS work as well as envisioned, might have been the question of how to make GPS available to the civilian community so they could share the benefits. The study claimed that the system was always offered for civilian use, albeit with some charge. After the Korean airliner went astray and got shot down by a Soviet interceptor aircraft, President Reagan made GPS officially available for civilian use free of charge. (O'Brien and Griffin 2007, p. 14)

The second challenge could be associated with preserving precision capabilities for the military only, and relegating course acquisition (C/A) accuracy to the civilian community. (O'Brien and Griffin 2007, p. 15) Later this dichotomy was essentially eliminated with the realization that a differential GPS configuration involving a fixed ground station with a precisely known location will yield great accuracy. (Kee, et al. 1991)

The GPS satellites used space-borne atomic clocks. To alleviate the need for updating these clocks too often, a successful effort was initiated to revise the international time standard which ended up using relatively infrequent "leap seconds". (O'Brien and Griffin 2007, p. 23) Even these are still annoying for many other applications, such as the continual need to achieve precise synchronization of frequency-hopping radios.

An organizational challenge of inter-service rivalries was overcome with the formation of the Joint Program Office (JPO). (O'Brien and Griffin 2007, p. 25.)

In the early days of satellite communication systems, for example, the satellites were quite small and low powered while the terminals were large and high-powered. By the time GPS came along, the satellites are getting bigger and more sophisticated. Then the challenge to develop relatively low-cost terminals, particularly for mobile users, greatly increased. (O'Brien and Griffin 2007, p. 29)

A small but interesting challenge was the definition of system of systems (SoS). It was decided that GPS was an SoS because it involved three independent systems, namely, the space vehicle (SV), the control segment (CS), and the user equipment (UE), that "merely" had to interface with each other. (O'Brien and Griffin 2007, p.

30)

Continually changing requirements is usually a problem, although in this case the requirements did not change as often as they could have. (O'Brien and Griffin 2007, p. 31)

Difficulties of defining and updating the many GPS interfaces was largely overcome by the GPS program director, Col. Brad Parkinson, when he convinced his own management, Gen. Schultz at Space and Missile Systems Office (SAMSO) (which eventually became the Space Division) that GPS ought to be defined solely by the signal-structure-in-space and not the physical interfaces. (O'Brien and Griffin 2007, p. 31)

Systems Engineering Practices

> Although the systems engineering process in Phase I has been discussed previously, this section will expand on the concepts. For example, one of the user equipment contractors was technically competent, but lacked effective management. The JPO strongly suggested that a systems engineering firm be hired to assist the contractor in managing the program and they agreed. (O'Brien and Griffin 2007, p. 42)

There did not seem to be any mention of what SE firm was hired, if any. The Aerospace Corporation, a non-profit Federally Funded Research and Development Center (FFRDC), which had such a key role in the run-up to GPS was also prominently and centrally involved in development phase of this humungous project. (O'Brien and Griffin 2007, pp. 20, 22, 25, 33, 34, 40, 41, 44, 48, 50-52, 56, 57, 62, 63, 64, 66, 67, 71)

Lessons Learned

> Communications was a key ingredient that was fostered throughout GPS development. (O'Brien and Griffin 2007, p. 71)

Yes, from reading the original case study there seems to have been a lot of cooperation among the various

organizations, more so than might have been expected in a less compelling case.

> Several precepts or foundations of the Global Positioning Satellite program are the reasons for its success. These foundations are instructional for today's programs because they are thought-provoking to those who always seek insight into the program's progress under scrutiny. These foundations of past programs are, of course, not a complete set of necessary and sufficient conditions. For the practitioner, the successful application of different systems engineering processes is required throughout the continuum of a program, from the concept idea to the usage and eventual disposal of the system. Experienced people applying sound systems engineering principles, practices, processes, and tools are necessary every step of the way. Mr. Conley, formerly of the GPS JPO, provided these words: "Systems engineering is hard work. It requires knowledgeable people who have a vision of the program combined with an eye for detail." (O'Brien and Griffin 2007, p. 72)

In very complex systems engineering efforts of this type, it is also important to explore new techniques that attempt to deal with "soft" issues involving people. Those that seem to work can be added to the systems engineering process collection.

> Systems engineering played a major role in the success of this program. The challenges of integrating new technologies, identifying system requirements, incorporating a system of systems approach, interfacing with a plethora of government and industry agencies, and dealing with the lack of an operational user early in the program formation required a strong, efficient systems engineering process. The GPS program embedded systems engineering in their knowledge-base, vision, and day-to-day practice to ensure proper

identification of system requirements. It also ensured the allocation of those requirements to the almost-autonomous segment developments and beyond to the subcontractor/vendor level, the assessments of new requirements, innovative test methods to verify design performance to the requirements, a solid concept of operations/mission analysis, a cost-benefit analysis to defend the need for the program, and a strong system integration process to identify and control the "hydra" of interfaces that the program encountered. The program was able to avoid major risks by their acquisition strategy, the use of trade studies, early testing of concept designs, a detailed knowledge of the subject matter, and the vision of the program on both the government and contractor side. (O'Brien and Griffin 2007, p. 72)

This well summarizes the successful systems engineering approach utilized in GPS. Another element of achieving overall balance is the pursuit of opportunities as the "flipside" of risk mitigation.

Finally, here is the list of academic questions offered in the original case study.

QUESTIONS FOR THE STUDENT (O'Brien and Griffin 2007, p. 73)

The following questions are meant to challenge the reader and prepare for a case discussion.

- Is this program start typical of an ARPA/DARPA funded effort? Why or why not?
- Have you experienced similar or wildly different aspects of a Joint Program?
- What were some characteristics that should be modeled from the JPO?
- Think about the staffing for the GPS JPO. How can this be described? Should it be duplicated in today's programs? Can it?
- Was there anything extraordinary about the support for this program?

- What risks were present throughout the GPS program. How were these handled?
- Requirement management and stability is often cited as a central problem in DoD acquisition. How was this program like, or [un]like, most others?
- Could the commercial aspects of the User Equipment be predicted or planned? Should the COTS aspect be a strategy in other DoD programs, where appropriate? Why or why not?

Other questions might be: What possible influences did the demand for or offering to the public of this GPS capability entail? What differences in the development of GPS might have emerged if the public was more aware of the potential applications for their benefit at the outset?

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Additional References

None

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