Toward Efficient and Effective Contracting Structures and Processes for Systems-of-Systems Acquisition

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Abstract. Acquisition of a system of systems can be an all new acquisition of multiple systems that are intended to operate together as a system-of-systems. Much more common in the DoD is acquisition of one or more new systems that are intended to interoperate with existing systems as a system of systems with new capabilities. In either case, successful acquisition of systems-of-systems (SoS) necessarily depends on effective contracting structures and processes for systems-of-systems acquisition. In this paper, a set of system-of-systems issues that need to be addressed in SoS acquisition are identified and the current findings in this on-going research are discussed. The findings suggest sustainment of extensive systems engineering effort within the SoS acquisition and change to the existing contracting structures and process and organizational structures to maximize the probability of SoS acquisition success. The resulting changes will be applied to current and future DoD SoS acquisitions.

Introduction

No universal agreement on a definition of the term 'system of systems' exists, but many definitions have common basic elements. Sage and Cuppan (2001) describe a system of systems (SoS) as having operational and managerial independence of the individual systems as well as emergent behavior. Maier and Rechtin (2002) describe systems of systems as systems with emergent behavior which are operationally independent, managerially independent, evolutionarily developed, and geographically distributed. Boardman and Sauser (2006) describe one of the differentiating characteristics of an SoS as autonomy exercised by the constituent systems in order to fulfill the purpose of the SoS. Other definitions include operational and managerial independence and geographical separations of the constituent systems. Two characteristics of the types of systems of systems normally considered in the U.S. Department of Defense (DoD) acquisition are that the constituent systems of an SoS are not chosen but rather mandated to belong to the SoS and that the SoSs are usually bounded. An SoS can consist of to-be-developed systems, existing systems, or some combinations of new and existing systems.

SoS acquisition in the U.S. DoD is faced with many challenges. Some SoS programs have faced technical and management challenges, if not failures. The U.S. Army's Future Combat System program (US Army, 2002) has a serious budget overrun (GAO, 2003 and 2007). The U.S. Coast Guard's Integrated Deepwater System suffers from the lack of collaboration between contractors and the system integrators' inability to impose decisions on them (GAO, 2006).

With an aim to develop approaches that can prevent such SoS acquisition programs from failing, Ghose and DeLaurentis (2008) look into "types of acquisition management, policy insights, and approaches that can increase the success of an acquisition in the SoS setting." They investigate the impact of SoS attributes, such as "requirement interdependency, project risk, and span-of-control of SoS managers and engineers—on the completion time of SoS projects. " Ghose and DeLaurentis (2008, 2009) cite "the common causes of failure (Rouse 2007) within SoS acquisition processes as: a) misalignment of objectives among the systems, b) limited span of control of the SoS engineer on the component systems of the SoS, c) evolution of the SoS, d) inflexibility of the component system designs, e) emergent behavior revealing hidden dependencies within systems, f) perceived complexity of systems and g) the challenges in system representation." In their work, they analyze the effect of requirement dependency, span-of-control and risk profiles on, as a success metric, the total time to complete the project. For example, they find that acquisition process completes in 19 time-steps with low span-of-control, as compared to 12 time-steps with high span-of-control. The concept of span-of-control of engineers and managers is also addressed in the work in this paper, as it is related to both the pre-~~acqusition~~acquisition and ~~acquisiton~~acquisition phases of SoS acquisition.

Osmundson *et al.* (2007) address SoS acquisition issues and their resolution by modeling and simulation, but with a focus on SoS systems engineering. These issues include initial agreement to operate as an SoS, SoS control, organization of the SoS, identifying SoS measures of effectiveness (MOEs) and measuring effectiveness, staffing, team building and training for SoS operation, identifying data requirements, identifying and managing interfaces, risk management, SoS testing and managing emergent behavior. Each of these issues is briefly discussed here. A detailed elaboration of these issues and their resolution by modeling and simulation are in (Osmundson *et al.*, 2008).

The work captured in this paper attempts to answer this question : Can new contracting concepts be developed to aid in maximizing the probability of SoS acquisition success? The usual systems acquisition success criteria apply: performance, schedule, and budget — systems to be developed within a desired schedule and within a budget and to perform according to requirements. Briefly, contracting refers to the federal government and DoD contract management policy and guidance, roles and responsibilities in DoD contract management. A detailed elaboration of these contracting elements can be found in (Rendon and Snider, 2008).

This paper treats a realistic scenario of an SoS acquisition program represented in Fig. 1 and 2. It is realistic in the sense that it reflects some current DoD SoS acquisition programs. Fig. 1 shows three separate, autonomous, individual systems (System A, System B, and System C). These systems are currently being acquired (researched, developed, tested, produced, and deployed). Each system is managed by a government program office and a contractor performing in accordance with the requirements of an acquisition contract. In this scenario, during the course of the acquisition of each individual system, a new mission arises and requires an SoS that consists of the three systems being built; the government thus adds a requirement that each individual system become part of the SoS acquisition program. Fig. 2 reflects the new SoS acquisition program. The shaded areas depict the SoS requirements that are imposed on the systems being developed. In this paper, the discussion of the contracting structures and processes for SoS acquisition pertains to this scenario.

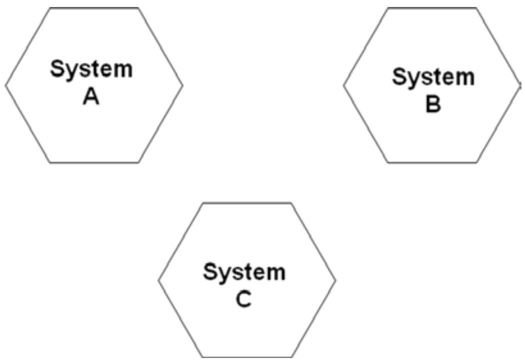

Figure 1. Three Separate Systems Being Developed

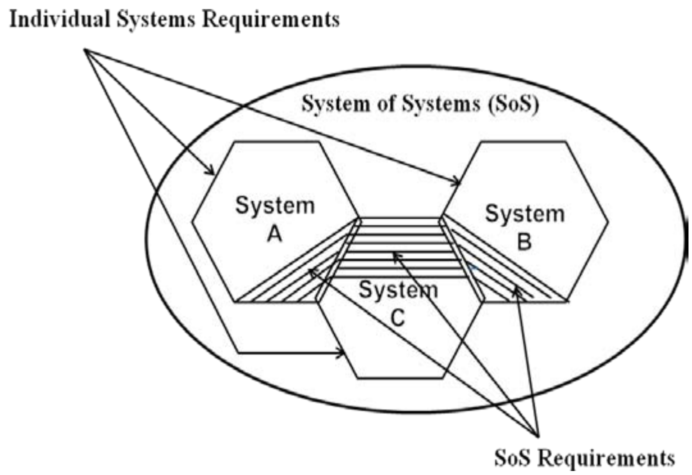

Figure 2. Addition of SoS Requirements

The transition from the acquisition of individual systems to the acquisition of an SoS has implications on the relationship between the government and the contractors. This relationship is also determined by the organizational structure used to manage the SoS acquisition program. Will the required SoS systems engineering be performed by a new, overarching group, by a collaboration among systems engineering organizations associated with existing systems, or by a single systems engineering organization associated with one of the component SoS systems? In addition to contracting, organizational structure is also discussed in this paper.

The goals of this paper are:

1. To emphasize the span-of-control of engineers on SoS acquisition during the SoS pre-acquisition and acquisition phases.
2. To examine all possible contracting options in conjunction with all possible organizing options.
3. To arrive at the possible combinations of contracting and organizing options for resolving the SoS acquisition issues.
4. To map resolution of SoS issues to the SoS acquisition success criteria.

The rest of the paper begins with a discussion of the SoS acquisition issues, follows with an examination of some SoS-acquisition related concepts, and ends with a conclusion.

Systems-of-Systems Acquisition Issues

Systems acquisition refers to the disciplined management approach for the acquisition of an individual system, such as a weapon system (aircraft, ship, missile, etc.) or an information technology system. The acquisition process involves the various activities related to the development, design, integration, testing, production, deployment, operations and support, and disposal of the system. Within the federal government, specifically the DoD, systems acquisition uses a program management approach to the management of these activities. This approach involves the use of a project lifecycle, which includes phases, gates, and decision-points, a project manager, and a project team (Rendon and Snider, 2008). This approach is envisioned to apply to SoS acquisition, but making use of some new concepts, discussed in this paper, as there are significant differences between systems and systems of systems (SoS) and these differences affect the nature of Government contracting for the development of systems of systems. Such application requires understanding of the issues associated with SoS acquisition.

The aforementioned SoS acquisition issues raised in (Osmundson *et al.*, 2008) are now briefly discussed here. In this paper the importance of SE endeavor ties to the SoS pre-acquisition and acquisition phases and to the contracting process is emphasized; that is, the span of control of the engineers is crucial in this SoS pre-acquisition and acquisition phases.

- *Initial agreement* refers to decision makers initially getting agreement that an SoS meets some desirable objective. It is an issue in particular when the SoS involves systems from different organizations or services because establishing an initial agreement is contingent on quantifying the benefits and risks of the new SoS.
- *SoS control* must be established: Who will control the SoS and how it will be controlled. Each partner may lose some measure of control over its own systems in order to enable overall SoS control.
- *Organizing* is a key issue of how to organize for the development and operation of an SoS. An example is the systems engineering process: How are processes that interface with SoS processes established and monitored?
- *Staffing, team building, and training* refer to how an SoS will be staffed and operated. SoS operations must be planned for, the skills required for SoS operations identified, and personnel with the proper skills acquired and trained in SoS operations.
- *Data requirements* is an issue concerning sharing of classified and/or proprietary design information among the SoS partners, who must recognize and weigh a possible loss of their ~~systems's~~system's operational superiority based on the shared classified or proprietary design information against the SoS benefits.
- *Interfaces* must be identified and managed. Common language, grammar and usage must be established (for information SoSs), configuration management invoked to assure common agreements are followed, and required information security levels identified and provisions made to assure meeting of security requirements.
- *Risk management* at the SoS level is an issue related to the mitigation of SoS risks potentially ~~effected~~affected by component systems, which requires detailed knowledge of component system risks and variations in individual system outputs.
- *SoS testing* requires each SoS partner's system be tested in a manner that resolves any of its concerns about operational behavior and SoS threads be tested.
- *Measures of effectiveness* is an issue because their strong dependence on individual component ~~systems's~~system's measures of performance requires an understanding of the latter, and this

issue is related to the issues of data requirements and interfaces.

- *Emergent behavior*, exhibited by the SoS resulting from unknown interactions among the constituent systems or from its interaction with the environment, need be collectively understood, analyzed, and resolved, in particular when an emergent behavior may be detrimental to one or more of the partners.

Some SoS-Acquisition Related Concepts

What contracting and organizing options can be used to aid in resolving the SoS issues ? This section discusses these options and the correspondence of their combinations and the SoS issues.

Cross-functional Team Model. As previously stated, government systems acquisition management involves the use of project teams. The project team is a cross-functional team, consisting of technical specialists from the various functional areas involved in the acquisition process. These functional areas typically include systems engineering, contract management, financial management, logistics, and others. The cross-functional team is led by the government program manager. The program manager has overall responsibility for the success of the acquisition project. Although the program manager has overall responsibility, the program manager may not have all of the authority needed to manage the program. For example, the contracting officer may have the specific authority to award and make changes to the contract. Most systems acquisition programs involve effort performed by a contractor with the contract managed by the government program office. The contractor will generally have its own program manager and cross-functional team managing the contract for the contractor. Daily communication and coordination between government and contractor program managers, system engineers, and contract managers is the norm in defense acquisition management (Rendon and Snider, 2008). This paper is focused on systems engineering and contract management of the cross-functional team.

SoS Systems Engineering. The concept of span of control on the system components is crucial in all phases of acquisition. This means that systems engineering discipline need be enhanced and ever present in the SoS pre-acquisition and acquisition phases. Toward this end, there are two possible approaches. One is having a capable SE organization strictly organic to the SoS acquisition program office, and the other is using a capable SE organization external to the SoS acquisition program office, but the latter has strict ownership of the SE organization during the entire SoS acquisition. The advantages of the first approach are that the span of control of the engineers takes hold, direct control or exchanges are facilitated, and independence from contractors' undue influence materializes. The disadvantages are investment in money and people. The second approach suffers from control and increased in budgets for the same service required of the former, and time spent on establishing contracts to have an external organization to support.

Whereas this concept is not new, this paper calls for it to be instituted and for the span of control to exist during the pre-acquisition and acquisition phases.

Contracting Options. The transition from the acquisition of individual systems to the acquisition of an SoS has implications on the relationship between the government and the contractors. This relationship is largely determined by the contracting structure and processes governing the SoS requirements. There are three options for incorporating the SoS requirements into the individual acquisition programs (Programs A, B, and C in the scenario): Two separate contracts; replacement of the existing contract; and modification of the existing contract. The discussion of each of them follows.

The first option is to incorporate the SoS requirements (shaded areas of each system in Fig. 2) as a contract distinct from the existing contract for each contractor. Contractors A, B, and C would receive an additional contract with the specific SoS requirements for that specific system. In this option, each contractor would be working under two different and separate contracts—one for the acquisition of the basic system, and one for the SoS requirements related to the basic system.

The second option is to terminate the original contract for the acquisition of the individual system and to negotiate and award a new single contract for both the acquisition of the single system and the acquisition of the SoS components of that system. In this option, each contractor remains with only one contract.

The third option is to negotiate a modification to the existing contract, which incorporates the SoS requirements for that system under the existing contract. In this option, the contractor also remains with a single contract, albeit a modified contract, for all acquisition requirements.

This paper suggests that the third contracting option, modifying the existing contract to incorporate the SoS requirements, would be preferred over the first option, since having a contractor work under two separate contracts may be problematic. For example, there is a risk that the two contracts may be in conflict with each other, such as conflicting specifications, statements of work, or schedule priorities. The resources required for administering two separate contracts would be an disadvantage. Furthermore, managing two separate contracts would complicate organizational structures (discussed below). The third option would be preferred over the second option because modifying an existing contract is more advantageous than negotiating a termination agreement on the original contract and then negotiating a new contract with the contractor. During these negotiations, it is likely that the contractor would need to stop the acquisition effort, thus impacting the project schedule and cost.

The preferred contracting option, modifying the existing contract to incorporate the SoS requirements, is not without issues. First, time and resources are still needed to add modifications to the existing contract. Second, the preferred option is predicated on the assumption that the set of added SoS requirements is relatively smaller than that of the original system requirements. If the added SoS requirements constituted a major portion of the total requirements or exceeded the existing requirements, then replacing the existing contract would be a preferred option. Finally, care must be taken to ensure that the modified contract will not be used as a device to correct the contractual weaknesses discovered after the existing contract is in place.

Organizational Structure Options. Different SoS acquisition contracting options bear some impact on SoS acquisition program organizational structures. As previously stated, the transition from the acquisition of individual systems to the acquisition of an SoS has implications on the relationship between the government and the contractors. This relationship is also determined by the organizational structure used to manage the SoS acquisition program.

In structuring the organization, three options can be used for the SoS acquisition program. The first option is to designate one of the individual programs as the lead program and make that government program office responsible for managing the entire SoS acquisition program, which includes the other two systems. For example, the government program office managing System A could be designated the lead program and made responsible for ensuring systems (A, B, and C) meet the SoS requirements. Thus the government program manager for System A will also have SoS acquisition responsibility and authority over the government program managers for System B and System C.

The second option is to establish a separate government program office responsible for the SoS acquisition program. This separate government program office would have SoS acquisition responsibility and authority over the three individual government program offices managing their individual acquisition programs (System A, System, B, and System C.) In this option, the SoS acquisition management would be performed by in-house government acquisition and contracting workforce.

In the third option, a contractor is selected to manage the acquisition of the SoS program. This contractor, typically referred to as a Lead Systems Integrator, would oversee the SoS requirements within the three individual systems (A, B, and C). This option entails awarding a contract to a company to perform the SoS acquisition management.

This paper suggests that the second organizing option, establishing a separate government program office responsible for the SoS acquisition program, would be preferred over the first organizing option, since having one of the individual programs as the lead program and making that government program office responsible for managing the entire SoS acquisition program would result in potential conflicts of interest. The government program manager for the individual program may be biased and improperly influenced in the management of the overall SoS acquisition program. In this position, the government program manager may favor the individual program over the needs of the SoS.

The second organizing option would be preferred over the third organizing option because having a contractor manage the SoS acquisition program may involve the contractor performing some of the critical requirements determination and acquisition decision-making of the SoS program. The third contracting option may result in the out-sourcing of inherently government functions related to the acquisition of the SoS program. It may also result in the government's loss of a systems engineering core competency and capability for managing SoS programs.

The implementation of the second organizing option requires clearly defined policies governing reporting and responsibility relationships among the different program managers in the government. Not only must the issue regarding individual system program managers reporting to more than one master be resolved, but the issue regarding the relationships among peer individual system program managers must also be addressed. Confusion and chaos resulting from undefined or misunderstood relationships would impediment the management of the integration of the SoS, hence the success of the SoS acquisition as well as that of the acquisition of the individual systems. A future publication will address these issues and the implementation of the second organizing option.

Linkages between Contracting Options and Organizational Structure Options. A logical linkage appears to exist between the preferred contracting and organizing options for transitioning from the acquisition of individual systems to the acquisition of an SoS. The preferred contracting option of modifying the existing contracts to incorporate the SoS requirements and the preferred organizing option of establishing a separate government program office responsible for the SoS acquisition program can be effectively implemented together. The government program office responsible for the acquisition of the SoS would be the requirements agency for the SoS program. In this capacity, the SoS government program office can communicate the SoS requirements to each system program office. The system program office would then incorporate these requirements into the individual system contract modification. The systems engineering and contract management personnel from the SoS government program office would communicate and collaborate with the systems engineering and contract management personnel in each of the individual system program offices to manage these SoS requirements.

One potential drawback to the linkage of the two preferred contracting and organizing options would be the conflict potential between the SoS government program manager and the individual system government program manager (such as between the SoS government program manager and System A government program manager). This would occur in situations dealing with cost, schedule, and performance priorities between the two aspects of the system (individual and SoS). The understanding of and adherence to roles and responsibilities between the SoS government program manager and the individual system program manager, as well as an order of precedence clause in the contract, would help deter these potential conflict situations.

Table 1 shows a number of possible combinations of contracting and organizing options, which, marked with '√', potentially result in the resolution of the SoS issues, which, in turn, enables satisfaction of the SoS acquisition success criteria (marked with 'X'). As discussed above, the preferred contracting option for the scenario of interest is the replacement of the existing contract. It can be combined with either the separate government program option, which is, as discussed above, the preferred option or the lead systems integrator option. For example, given that the existing contract is replaced by a new one, either the separate government program option or the lead systems integrator option, the SoS interfaces issue should be resolved. The resolution of such an issue would enable the satisfaction of the SoS acquisition criteria.

Table 1. Resolution of SoS Issues by Option Combinations and Satisfaction of Acquisition Success Criteria

	Contracting Option			Organizing Option			Acquisition Success Criteria		
Issues	Two separate contracts	Replacing contract	Modified contract	Designated individual program	Separate government program	Lead Systems Integrator	Performance	Schedule	Budget
Initial agreement .			√		√	√	X		
SoS control					√	√	X		
Organizing			√		√	√	X	X	X
Staffing, team building, and training			√		√				X
Data requirements			√		√		X	X	
Interfaces			√		√	√	X	X	X
Risk management			√		√	√	X	X	X
SoS testing			√		√	√	X	X	X
Measures of effectiveness			√		√	√	X	X	X
Emergent behavior			√		√	√	X		

Conclusion

The purpose of this on-going research is to determine contracting and organizational options to enable successful SoS acquisition and to apply them to current and future DoD SoS acquisitions.

At this point in ~~this~~ the research, the following is suggested:

- Sustainable systems engineering effort with an extensive span of control by systems engineers within an SoS acquisition is necessary for a successful SoS acquisition.
- Among the possible contracting options, modifying the contract is the preferred option. But that's not sufficient. Organizing options must be considered, for an organizing option must be coupled directly with a contracting option and, together, they would enable resolution of the SoS acquisition issues, which, in turn, could improve the probability of SoS acquisition success, and thereby facilitating and effectively managing the SoS acquisition effort.

These findings will be applied to a case study, whose supporting data and results will be published in a future paper. Furthermore, a separate paper will invoke a collaboration theory and incorporate it in the organizing options in particular and in SoS acquisition in general (Huynh *et al.*, 2010). It will address the implementation of the second organizing option and its related issues.

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He is an associate professor of systems engineering at the Naval Postgraduate School in Monterey, CA. His research interests include uncertainty management in systems engineering, complex systems and complexity theory, system scaling, and system-of-systems engineering methodology. Prior to joining the Naval Postgraduate School in 2003, he was a Fellow at the Lockheed Martin Advanced Technology Center in Palo Alto and Sunnyvale, CA, where he engaged in research in computer network performance, computer timing control, bandwidth allocation, heuristic algorithms, nonlinear estimation, perturbation theory, differential equations, and optimization. While he spent 23 years in the aerospace industry, he was also teaching part-time in the departments of Physics and Mathematics at San Jose State University. Dr. Huynh is a member of INCOSE.

John S. Osmundson received a B.S. in physics from Stanford University and a Ph.D. in physics from the University of Maryland. He is an associate research professor with a joint appointment in the Systems Engineering and Information Sciences Departments at the Naval Postgraduate School in Monterey, CA. His research interest is applying systems engineering and computer modeling and simulation methodologies to the development of systems of systems architectures, performance models, and system trades of time-critical information systems. Prior to joining the Naval Postgraduate School in 1995, Dr. Osmundson worked for 23 years at Lockheed Missiles and Space Company (now Lockheed Martin Space Division) in Sunnyvale and Palo Alto, CA, as a systems engineer, systems engineering manager, and manager of advanced studies. Dr. Osmundson is a member of INCOSE.