CHALLENGES TO INNOVATION IN THE GOVERNMENT SPACE SECTOR

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This article uses innovation theory to identify five core challenges of generating national security space innovation: (a) generating bottom-up push in a top-down environment; (b) integrating fragmented buy-side knowledge; (c) integrating fragmented sell-side knowledge; (d) matching the innovation environment to the development stage; and (e) balancing risk aversion with the need for experimentation. An analysis of how the current two-tiered process, which separates technology development from project-based acquisition, addresses these challenges, reveals that this method of separation is not a complete solution because it: (a) fails to value architectural innovation; (b) creates a disaggregated knowledge base, which exacerbates the difficulty of top-down specification and bottom-up integration; and (c) fails to generate an entrepreneurial supply-side spirit. Recommendations for improvement are provided.

Keywords: *Innovation Theory, Monopsony-oligopoly Market, Space Acquisition, Spacecraft Development, Acquisition Process, Risk Aversion*

image designed by Miracle Riese »

Characteristics of the government space market, with its monopsony-oligopoly structure and complex robust products, make encouraging innovation challenging. The Department of Defense (DoD) acquisition structure represents one example of how these challenges are addressed in an institutional setting. However, a recent string of failures has brought into question the efficacy of the system. Multiple blue ribbon panels have been convened leading to recommendations about how the current system can be improved; however, these recommendations take certain implicit assumptions of the system as a given. If a major reform is to be achieved, these fundamental assumptions must be reviewed. This article takes a step back from the acquisition process, using innovation theory to assess the intrinsic challenges of encouraging complex product innovation in a government monopsony-oligopoly. In particular, it seeks to answer the following questions: (a) What are the implications of the space sector characteristics on innovation? (b) How (or to what extent) does the acquisition system address these implications? and (c) How can these insights be used to improve acquisition in the space sector?

Implications of Space Sector Characteristics for Innovation

Despite a rich legacy of delivering impressive technology, defense acquisitions are increasingly characterized by schedule slips and cost overruns. With long development times and high complexity, national security space systems (e.g., Advanced Extremely High Frequency [AEHF], National Polar-orbiting Operational Environmental Satellite System [NPOESS], Space-Based Infrared System–High [SBIRS–High], Global Positioning System [GPS] II) have become particularly illustrative of the challenges confronting defense acquisitions (Government Accountability Office [GAO], 2007). In recent years, in an effort to address these problems, multiple blue ribbon panels have been convened. Figure 1 enumerates the recommendations of six recent reports along technical, management, and policy dimensions.

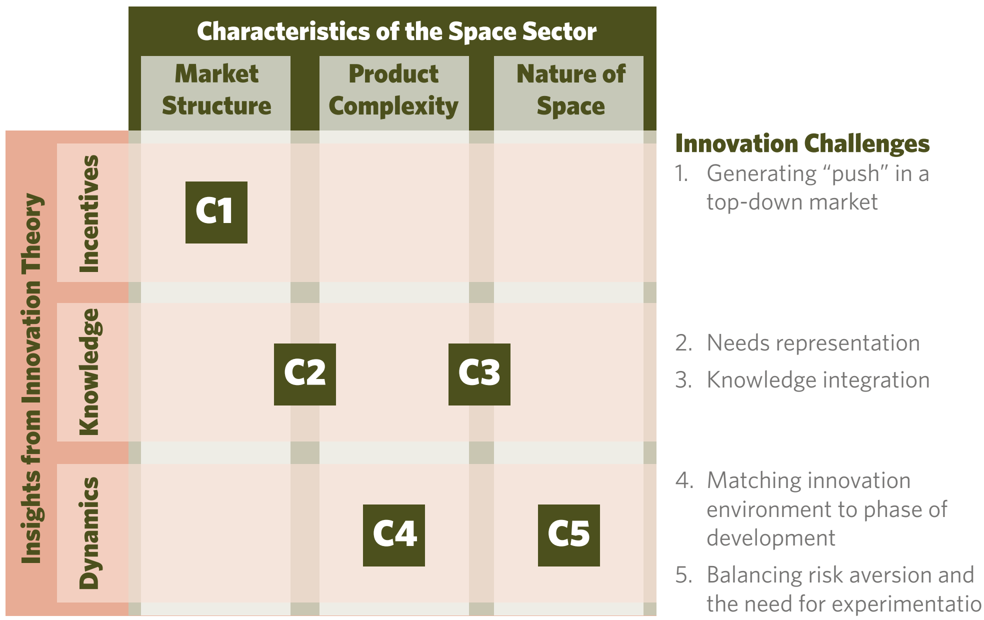
Bringing to bear the members' vast experience working in the current acquisition paradigm of large monolithic spacecraft, their recommendations emphasize a back-to-basics philosophy (i.e., maturing payload technologies outside of acquisition programs). However, with the rapidly changing requirements that characterize the needs of today's warfighter, it may be the acquisition paradigm itself that needs fixing.

FIGURE 1. KEY FINDINGS FROM RECENT STUDIES

		Rumsfeld (2001)	NDIA (2003)	Young (2003)	GAO (2006)	DoD (2006)	NRC (2008)
technology	Restore funding for testing space technologies	X			X		
	Maintain U.S. technological lead in space	X					
	Keep R&D separate from systems acquisition				X		X
	Identify technology for rapid exploitation and control						
management	Establish Presidential and NSC space advisory groups	X					
	Integrate defense and intelligence space activities	X					
	Improve front-end systems engineering (req's=resources)		X	X	X	X	X
	Improve collaboration on requirements		X		X	X	X
	Budget space programs to most probable (80/20) cost			X			
	Evaluate contractor cost credibility in source selections			X			
	Conduct independent program assessments at MDA's			X			
	Do not allow requirements creep			X	X	X	X
	Match PM tenure with delivery of a product			X	X	X	X
	Pursue incremental increases in capability				X		
	Withhold contractor award fees when goal is not met				X		
	Establish a stable program funding account					X	
	Structure development to achieve IOC within 3–7 years						X
policy	Recognize space as top national security priority	X					
	Deter and defend against hostile acts in space	X					
	End practice of appointing only flight-rated CINCSPACE	X					
	Incentivize government career paths in acquisitions	X	X	X		X	X
	Improve workforce technical competence	X		X	X	X	X
	Research systems architecting design tools		X				
	Establish mission success as guiding principle			X			
	Compete acquisitions only when in best interest of gov't			X			
	Develop integrated strategy for R&D and acquisitions				X		X
	Encourage LSI to compete major subsystems					X	
	Evaluate gov't internal training programs for acquisition						X

Note. CINCSPACE = Commander in Chief, Space Command; gov't = government; IOC = Initial Operating Capability; LSI = Lead Systems Integrator ; MDA = Milestone Decision Authority; NDIA = National Defense Industrial Association; NRC = National Research Council; NSC = National Security Council; PM = Program Manager; R&D = Research and Development; req's = requirements. Adapted from DoD, 2006; GAO, 2006; GAO, 2007; NDIA, 2003; NRC, 2008; Rumsfeld et al., 2001; Young, Hastings, & Schneider, 2003.

FIGURE 2. OVERVIEW OF INNOVATION CHALLENGES FOR DEFENSE ACQUISITIONS

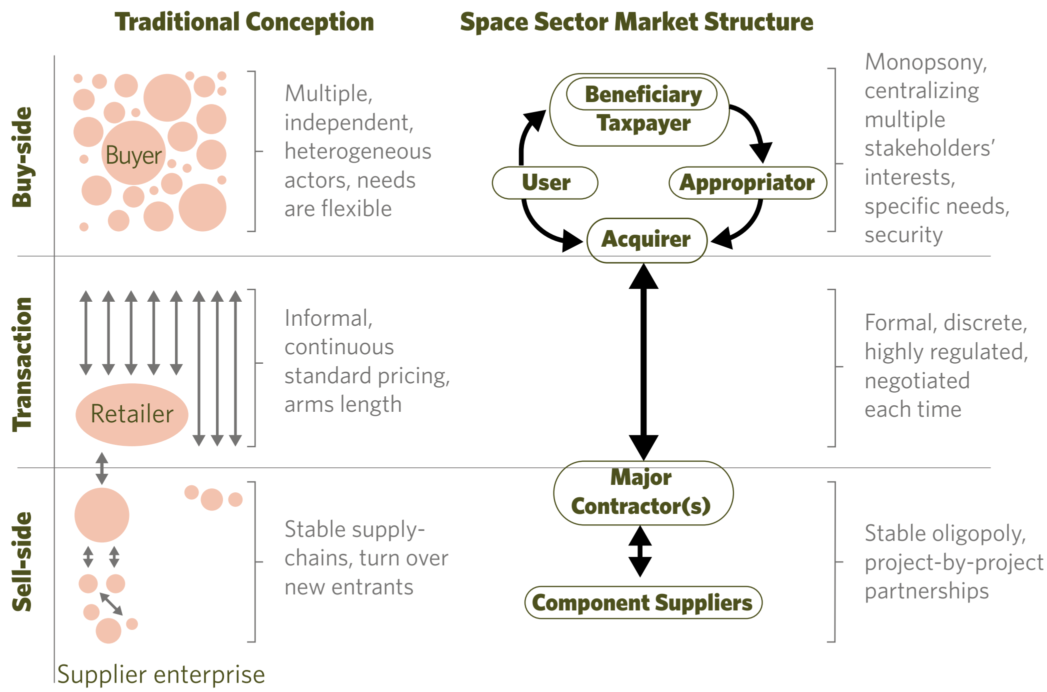


By applying strategic prescriptions on how innovation should be encouraged (as abstracted from the management and innovation literatures) to intrinsic characteristics of the space sector, five fundamental challenges to innovating in the space sector were identified: (a) generating bottom-up push in a predominantly top-down acquisition process; (b) representing the needs of a disaggregated buyer; (c) integrating fragmented sell-side knowledge from the top-down; (d) matching the innovation environment to the stage of development; and (e) balancing risk aversion and the need for experimentation. Figure 2 provides an overview of these five challenges. The following sections explain the nature of each challenge.

Challenge 1: Generating Bottom-Up Push in a Predominantly Top-Down Acquisition Process

Taking a classical economic view of innovation, market transactions are thought to be the fundamental driver of innovation. Innovation[1] occurs over time through the interaction of user needs (market pull) and seller capabilities (product push) (Rothwell & Zegveld, 1994). In a competitive market, this process happens naturally. Both the consumer's willingness to pay and the supplier's ability to deliver are revealed continuously through the mechanism

FIGURE 3. COMPARISON OF SPACE AND TRADITIONAL MARKET STRUCTURES



of price (Adams & Adams, 1972). However, in the space market, which consists of only one buyer and few sellers, the interaction only occurs when the monopsony buyer expresses a need. As a result, the transaction is less effective as a mechanism for revealing preference-capability information.

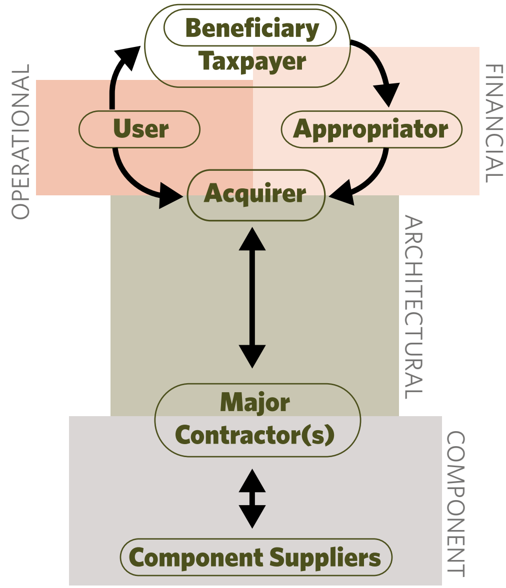
Figure 3 illustrates the differences between the two market types. Since monopsony markets are discrete (i.e., the market only exists when the buyer wants to buy), buyer needs must be revealed explicitly as they arise. If major performance improvements are required of each new acquisition, as is typically the case between generations of spacecraft, radical innovation must occur in discrete intervals, upon request. Since the request for radical change originates from the government buyer, so too does much of the investment in product development for space applications (Sherwin & Isenson, 1967). The market is dominated by a top-down "pull" to the near exclusion of the complementary bottom-up "push." This is a problem because a fertile innovation environment requires the presence of both forces, especially since most new ideas come from outside (Christensen, 2003). Thus, one of the key challenges to innovating in the space market is for the government to encourage bottom-up initiative.

Challenge 2: Representing the Needs of A Disaggregated Buyer

The existence of a top-down acquisition process could theoretically generate ideal conditions for innovation. In a discrete and specific process as previously described, only products that the buyer wants would advance to the development stage. This is ideal, assuming the buyer knows the precise product specifications. However, when the buyer is a monopsonist as complex as the U.S. Government, incorporating multiple disaggregated interests, this assumption may be invalid.

As illustrated in Figure 4, in the government acquisition context the monopsonist buyer—which encompasses the warfighter, the appropriator, acquirer, and taxpayer—is not a single coherent decision maker. The monopsonist exists to centralize both resources and expertise. As a result, since the acquirers (who do the actual choosing) must integrate **operational** (warfighter's expertise) and **financial** (appropriator's knowledge and taxpayer resources) trades to determine what next to buy, the decision will only be as good as their imperfect information. Therefore, unless buyer needs are well represented, delivery only of the product specified in the request for proposal may not be efficient at all.

FIGURE 4. OVERLAY OF KNOWLEDGE AREAS ON SPACE ACQUISITION MARKET STRUCTURE



Challenge 3: Integrating Fragmented Sell-Side Knowledge from the Top-Down

In addition to knowing what it wants, efficiency in a top-down acquisition process also requires that the buyer knows what is possible. In a commercial setting, typically a range of products exists from which to choose. Even when buying for a third party, a history of revealed preferences vis-à-vis similar products provides a reasonable basis upon which to make selections. However, in the case of acquirers buying for warfighters, the acquirers have only ever seen the warfighters use other systems that were also bought for them. While this intensifies the acquirers' challenge, it also presents a unique opportunity for the monopsony buyer (as a whole) to take a long-term, coherent perspective on driving innovation to their benefit.

However, knowing what is possible is particularly difficult in the realm of complex engineering products because they require the integration of so many different types of knowledge. For example, a *simple* communication satellite requires the technical expertise of thermal, power, solar, control, software, structural, and electrical engineers among others. In the time between successive acquisitions (often 10–20 years), advances will have likely been made in each discipline, as well as at the system level. In order to manage this complexity, prime contractors whose primary expertise is systems integration (i.e., architectural knowledge of how the pieces fit together) have emerged. They bid for whole contracts and farm out much of the subsystem development effort (component knowledge). This has led to a hierarchical fragmentation of the knowledge required to know what *should* come next and generate radical innovation (Henderson & Clark, 1990). The result, as shown in Figure 4, is that acquirers are not in a strong position to make this determination; sell-side input is needed.

Challenge 4: Matching the Innovation Environment to the Stage of Development

Utterback and Abernathy (Utterback, 1994; Utterback & Abernathy, 1975) have shown empirically that a relationship exists between maturity of the product undergoing innovation and characteristics of the organization in which the innovation occurred. Dividing the innovation process into three phases—fluid, transitional, and specific—they argue that free experimentation and a diversity of ideas are important ingredients for the fluid phase (e.g., inventors working out of their garages), while increasingly rigid organizational processes become appropriate as the product matures (e.g., a promising idea gets bought out and commercialized by a larger firm). The differences between the organizational environments are summarized in Table 1.

Having multiple, different innovation environments is particularly important for space systems because of their inherent complexity. Space systems decompose into subsystem elements, which decompose into component elements, etc. At each level of integration, innovation can be achieved through improvements to the element itself, or the way in which it interacts with other elements. Both types of innovation are required to achieve radical change, as illustrated in Table 1 (Utterback, 1994). Thus, in addition to the fluid, transitional, and specific phases defined by Utterback and Abernathy, spacecraft development may require additional variants to deal with both the component and architectural dimensions of innovation[2] (Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008). Yet, since spacecraft are developed as a single project, a single organizational environment exists throughout the formal process. As a result, a key challenge involves creating an organization that supports multiple innovation environments simultaneously.

Challenge 5: Balancing Risk Aversion and the Need for Experimentation

Perhaps the biggest difference among the three phases is the extent to which innovation can be planned. Once a dominant design emerges (in the transitional phase), innovation can be achieved by systematically making incremental improvements along particular dimensions, but until that point, there is much less certainty about what will work. In the transitional and specific phase, increasingly formal organizational structures are put in place, and those structures facilitate the optimization aspect of the innovation process. Conversely, the fluid phase start-ups have very little in the way of organizational structure, in part because no consensus has yet emerged on how the creativity is best encouraged (Fagerberg, Mowery, & Nelson, 2005). Another reason is that many innovations fail to make it out of the fluid phase. Most successful entrepreneurs failed several times before they succeeded, and fail again many times afterward. These are not risks that big companies typically take; such bold risk taking requires an undying belief in one's product that is often associated with entrepreneurs (Casson, Yeung, Basu, & Wadeson, 2006). As a result, society does not have a high expectation for the success of start-ups, and their failure is not remarkable. This is not the case for space systems.

Despite the fact that many new spacecraft are, for all intents and purposes, prototypes (i.e., inventions) at the system level, a high level of risk aversion characterizes the U.S. space architecture. Many reasons are cited for the conservatism that exists in the sys-

TABLE 1. RELATIONSHIP OF ORGANIZATIONAL STRUCTURE TO PRODUCT MATURITY

	1	2	3	4	5
Challenge	**Generating bottom-up innovation**	**Representing the needs of a disaggregated buyer**	**Integrating fragmented sell-side knowledge**	**Matching innovation environment to stage of development**	**Balancing risk aversion and experimentation**
Guidelines for improvement	Generate sell-side **initiative**, not just capabilities development	Increase emphasis on flowing needs to requirements	Create more opportunities for interaction through frequent acquisitions	Create additional organizational tiers spanning both the dimensions of product hierarchy and maturity	Shelter advanced spacecraft from failure-is-not-an-option mentality

tem. Unlike most terrestrial systems, once a spacecraft is launched, if systems fail or problems arise, fixing them is extremely difficult. Additionally, the act of launching the system, which is the only way to really test its survivability in the harsh environment of space, is extremely expensive. Thus, an extremely high premium is placed on getting it right the first time. In part because spacecraft tend to be so expensive, failure is accompanied by a high political cost. Unlike in the fluid phase of traditional markets, where inventors receive little attention until they succeed, space projects are highly visible. What's more, the public has little appreciation for the experimental nature of most first flights, reinforcing the need to succeed the first time. However, if innovators are to continue surfacing and developing radically different solutions, the need to shelter them from the constraining pressures of success becomes an imperative.

DoD Approach to Addressing the Challenges of Spacecraft Innovation

Although the DoD acquisition framework was not explicitly designed to address the five challenges previously presented herein, it does address each to some degree. This section describes the nature of the interaction.

Challenge 1: The Challenge of Generating Bottom-up Push in a Top-down Structure is Addressed Directly

The DoD acquisition process employs a two-tiered organizational structure focused on (a) research and development, and (b) formal acquisition programs. Initial technology development within the DoD is conducted by the Service Laboratories (e.g., Air Force Research Laboratory, Naval Research Laboratory, Army Research Laboratory) and several science and technology organizations such as the Air Force Office of Scientific Research, the Office of Naval Research, and the Defense Advanced Research Projects Agency. The technology development tier ensures that capabilities that will be needed in the future are under development today. The approach is relatively successful in generating new technologies, but is limited in two important ways. First, it places a disproportionately high cost and risk burden on the government since it is still an internal organization writing the specifications. Second, a manufactured push (as is the case here) is not the same as a true bottom-up push. Where the latter embodies the results of multiple organizations competing with each other to find the best solution, the former remains a response to a request for progress on a particular technology.

Challenge 2: The Challenge of Representing the Needs of a Disaggregated Buyer is Nominally Addressed Through the Functions of the Joint Capabilities and Integration Development System (JCIDS) Process

JCIDS constitutes the formal DoD procedure for the establishment of acquisition requirements and evaluation criteria for future defense programs, and aims to assess all available alternatives for meeting a validated warfighting need. In so doing, JCIDS seeks to integrate the preferences of multiple stakeholders in the defense establishment by examining perceived capability shortfalls or gaps of the combatant commanders or Secretary of Defense. In theory, JCIDS should address the challenge identified as Challenge 2 exactly; but, in practice the complexity of integrating the needs of such a disaggregated buyer as the U.S. Government leads to significant shortcomings in practice. While the DoD has significant experience translating requirements into products, the department is less effective at flowing needs into requirements—the crux of Challenge 2.

Challenge 3: The Challenge of Integrating Fragmented Sell-side Knowledge has Been Addressed Differently Over the History of the Space Age

Initially, significant in-house technical expertise was cultivated among government buyers, and significant oversight spanning the entire sell-side supply-chain was common practice. The government buyer adopted the risk through cost-plus contracts but retained design authority, thus giving them the ability to intervene when contracts were not being executed as desired. More recently, as cost control became a primary focus, the role of system integrator has been delegated to industry contractors, with technical development subsequently delegated to subcontractors. The idea was that profit-maximizing firms will allocate resources more efficiently. However, in practice the interests of industry do not always align with those of the government, limiting the effectiveness of the relationship. Coupled with the fact that the delegation of the oversight role has led to a decrease in the technical competency of the acquisition corps (NRC, 2008), this trend has exacerbated the challenge of integrating sell-side knowledge rather than helped.

Challenge 4: The Challenge of Matching the Innovation Environment to Stage of Development is Partially Addressed by the Two-tiered Acquisition Structure, in that Technology Development is Separated from Formal Acquisition

As illustrated in Table 2, this separation of the product development into only two phases makes sense if technology development

TABLE 2. RELATIONSHIP OF ORGANIZATIONAL STRUCTURE TO PRODUCT MATURITY

	Fluid	Transitional	Specific
Innovation Characteristics	Product changes/radical innovations	Major process changes, architectural innovation	Incremental innovations, improvements in quality
Organizational Characteristics	Entrepreneurial, organic structure	More formal structure with task groups	Traditional hierarchical organization
Process Characteristics	Flexible and inefficient	More rigid and changes occur in large steps	Efficient, capital-intensive, and rigid

Product Maturity ⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯>

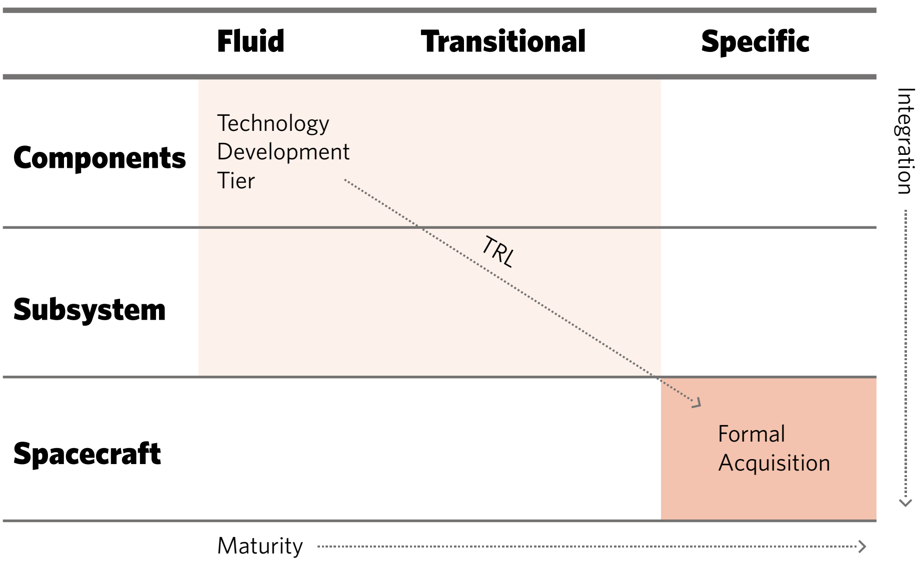
at the component and subsystem levels may proceed linearly to spacecraft-level system integration. However, as discussed previously, TRL is only one component of product maturity. Product maturity is also driven by architectural knowledge that may be measured by a system's readiness for integration. Developing new technologies for components and subsystems may actually *decrease* product maturity because of its ability to modify architectural knowledge of the system. Table 3 presents a more realistic representation of the evolution of product maturity. While formal technology development processes mature technologies in the fluid phase up to the subsystem level of integration, only at the spacecraft level is integration of the constituent technologies addressed. In other words, the formal acquisition process (which has the organizational characteristics of the specific phase) is forced to develop and integrate technologies that are far from specific in terms of maturity.

Challenge 5: The Challenge of Balancing Risk Aversion and the Need for Experimentation Faces a Similar Partial Fix

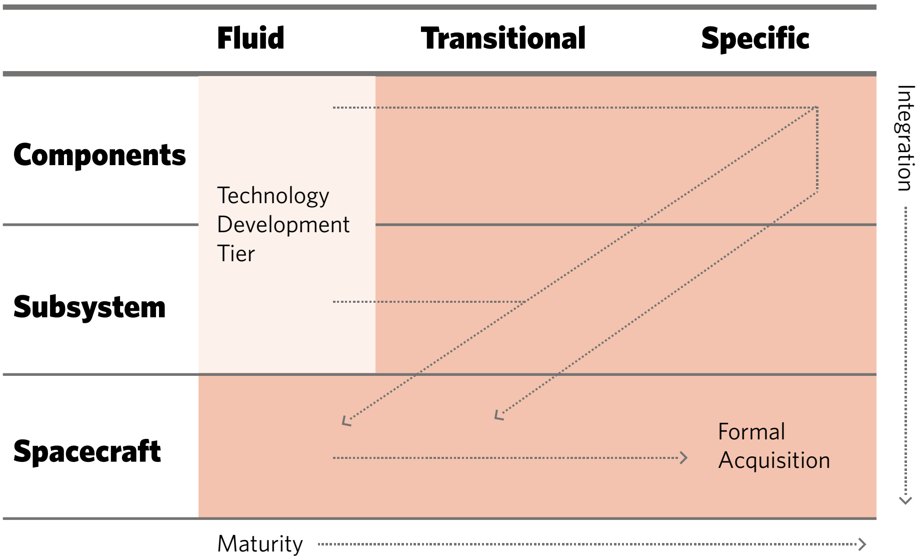
While the technology development tier serves to shelter R&D and component maturation from the public eye, no such shelter currently exists for the whole space system.

TABLE 3. TECHNOLOGY DEVELOPMENT PATHS

a.) Theoretical Two-Tiered Progression



b.) Implementation of Two Tiers



Guidelines for Improving Innovation in the Spacecraft Acquisition System

Over the last decade, multiple blue-ribbon panels have been convened to address known problems with the acquisition system. The key insights from these reviews are summarized in Figure 1. Building on the recommendations therein, this section highlights improvements that would specifically address the five core challenges to space sector innovation, as identified previously. These recommendations are summarized in Table 3.

From an innovation theory point of view, in Challenge 1—generating bottom-up innovation—the space market structure inhibits half of the natural competitive market innovation dynamic. As a result, until more buyers become involved in the space market,[3] any acquisition system will need a mechanism through which to ensure that new ideas continue to be infused into the acquisition system. Development contracts do accomplish this *capability development* to a certain extent, but as discussed previously, they are limited in their ability to encourage *sell-side initiative* and the parallel and varied concept explorations it embodies. Several other models exist for encouraging and leveraging sell-side initiative including commercial off-the-shelf, seed-funding models being explored by the Operationally Responsive Space program office and prizes (e.g., Ansari X-Prize). The idea in each of these is to help sustain a market rather than subsidize the development of a particular technology (i.e., generate sell-side initiative, not just capability development).

With regard to Challenge 2 (needs representation) and Challenge 3 (knowledge integration), the blue ribbon panels are almost unanimous in their recommendations to increase the technical competence of the Defense Acquisition Workforce and emphasize the importance of front-end specification. However, this only addresses half of the problem. No matter how many new capabilities are generated, their value will hinge on how well the original need was represented as a set of requirements. For the other half of the problem to be fully resolved, more emphasis must be given to the challenge of knowledge integration on both the buy- and sell-side. Specifically, with respect to Challenge 2, increased emphasis must be placed on flowing needs to requirements. This will involve a combined effort to educate users about their choices (what is possible) and help acquirers capture their needs more effectively. To this end, value-based system analysis methodologies to facilitate the process of capturing both articulated and unarticulated needs, early in the conceptual design phase, are currently being developed by researchers. Taking the value-centric perspective during conceptual design empowers stakeholders to rigorously evaluate and to compare different system requirements in the technical domain using a unifying set of attributes in the value domain (Mathieu & Weigel, 2005; Ross, Hastings, Warmkessel, & Diller, 2004). If deployed by system program offices, these emerging system analysis methodologies will contribute significantly to overcoming Challenge 2.

Overcoming Challenge 3 will require more frequent interactions among contractors, integrators, and the government through formal acquisitions. Where need-capability information is transferred continuously from buyers to sellers and vice versa, in traditional markets the transfer only happens during contracted hardware development in the space sector. As long as space acquisition continues to operate on a model of infrequent, extremely complex

monoliths, the knowledge required to innovate will continue to be fragmented across the various players. Decreasing the acquisition cycle time will not only help the knowledge integration problem identified in Challenge 3, but also the risk aversion in Challenge 5.

Challenge 4 (matching) identifies a fundamental limitation of the current system. In the existing acquisition paradigm, the product development required to enable future missions is conceptualized as a linear progression from TRL 1–9. With this view in mind, the blue ribbon panels call for increased funding for technology testing. However, while increased funding for technology development is a needed step in the right direction, it only addresses part of the problem. It fails to appreciate the difference between architectural and component dimensions of knowledge and what that means for system-level maturity. If the rest of the problem is to be addressed, a need arises for more than two organizational tiers: one for each of the three phases, as well as the dimensions of component and architectural knowledge.

Similarly, the recommendations of the blue ribbon panels that pertain to Challenge 5 (risk shelter) emphasize a back-to-basics philosophy, which keeps R&D separate from system acquisition. This would serve to shelter component development from political pressures, but do nothing at the spacecraft level. For spacecraft-level development to receive the risk shelter that is required, a major philosophical shift is needed. In this case, a back-to-basics philosophy might mean a return to the CORONA paradigm (e.g., recall that 12 launches of the revolutionary CORONA photoreconnaissance satellite were required before a successful demonstration of film capsule recovery on the 13th flight [Wheelon, 1995]). In other words, if radical innovation is desired, advanced spacecraft technology must be sheltered from the ubiquitous failure-is-not-an-option mentality.

The challenges identified in this article are fundamental to generating innovation in the space sector; they will not be easily overcome. This detailed discussion of the challenges presented in this article provides some guidelines for how to approach solving their associated problems, and will require all stakeholders involved to come together to implement a solution.

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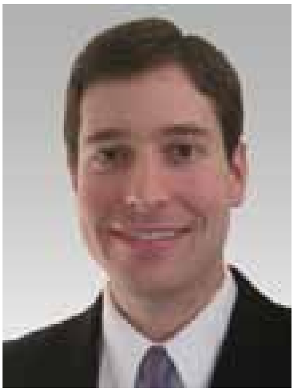

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ENDNOTES

1. For purposes of this article, innovation is defined as a measure of how performance, normalized by resource constraints, changes over time. This can involve either (a) generating a wholly new capability, or (b) reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter).
2. While component innovation is achieved through technology development and measured by technology readiness levels (TRL), architectural innovation may not be explicitly addressed by organizations. To support the formal specification of product maturity as a function of both component and architectural knowledge, Sauser et al. (2008) have proposed that a system readiness level be used based on both TRL and an integration readiness level (IRL).
3. This has happened, to a certain extent, in the domain of communication satellites and earth imaging and may soon be the case if space tourism were to take off, but is arguably unrealistic in the near future for more advanced and military applications.