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Implementation Challenges for Responsive Space Architectures

Matthew G. Richards
Massachusetts Institute of Technology
Building E38-550, 77 Massachusetts Ave; 617-324-4551
mgr@alum.mit.edu

Zoe Szajnfarber
Massachusetts Institute of Technology
Building 17-110, 77 Massachusetts Ave; 617-253-2428
zszajnfa@mit.edu

M. Gregory O'Neill
Massachusetts Institute of Technology
Building E38-505, 77 Massachusetts Ave; 617-324-4551
mgoneill@mit.edu

Annalisa L. Weigel
Massachusetts Institute of Technology
Building 33-404, 77 Massachusetts Ave; 617-253-1207
alweigel@mit.edu

ABSTRACT

Current space acquisition programs are often characterized by long-development cycles, cost overruns, and changing requirements. In an effort to match the time constants associated with space system development and operations to the needs of the system's respective users, operationally responsive space (ORS) architectures have been proposed. Fractionated spacecraft represent one potential architecture for achieving operational responsiveness. Fractionated spacecraft consist of physically independent, free-flying modules composed of various subsystems. These modules collaborate with one another on-orbit to provide a particular level of service delivery to the fractionated spacecraft's respective users. Although ORS architectures may sacrifice performance in traditional measures of effectiveness, ORS offers large potential improvements in matching the pace of change in user requirements with the timeliness of obtaining new capability on-orbit. While the purported benefits of ORS are well-documented in the literature, and technology development programs are already underway, there are several non-technical challenges that must be addressed as well. These challenges include aligning the economic incentives of stakeholders, integrating ORS into the current acquisition process, overcoming political inertia associated with legacy approaches, and ensuring that ORS capabilities complement existing architectures. Therefore, it is imperative that ORS development efforts account for the full-spectrum of challenges. Based upon a framework of technological, organizational, economic, and political challenges, implementation strategies for ORS are developed. These strategies are explored through an analysis of fractionated spacecraft as an example of an operationally responsive system.

KEYWORDS: operationally responsive space, fractionated spacecraft, innovation, acquisition, value

INTRODUCTION

> "There is nothing more difficult to carry out, nor more doubtful of success, nor more dangerous to handle, than to initiate a new order of things. For the reformer has enemies in all those who profit by the old order, and only lukewarm defenders in all those who would profit by the new order...[and because of] the incredulity of mankind, who do not truly believe in anything new until they have had actual experience of it."
> Machiavelli, The Prince, pp. 49-50

Given that large bureaucracies such as the Department of Defense (DoD) are not only hard to change but designed not to change,[1] successful development and transition of a radical innovation with uncertain future benefits constitutes a major challenge.

Operationally Responsive Space (ORS) has been defined broadly by the Department of Defense as "assured space power focused on timely satisfaction of Joint Force Commanders' needs... while also maintaining the ability to address other users' needs for improving the responsiveness of space capabilities to meet national security requirements."[2] As such, ORS is not only a program but a philosophy for improving the agility of space services to better address the dynamics of stakeholder needs and operational environments. In particular, ORS addresses the challenge of how flexibility, survivability, and other temporal system properties know as the "-ilities" might be better incorporated into the design and operation of space systems. When defined in this broad manner, several existing technologies may be classified as constituents of ORS (*e.g.*, TACSAT, on-orbit servicing).

One example of an ORS architecture early in its development is that of fractionated spacecraft at the Defense Advanced Research Projects Agency (DARPA). Fractionated spacecraft consist of physically independent, free-flying modules, each of which is composed of various "traditional" spacecraft subsystems. Thus, a fractionated spacecraft might be composed of one module for attitude control and propulsion, another module for the communications and telemetry subsystem, another module for power generation and storage, another module for the payload, and so on. An important attribute of fractionated spacecraft is their ability to decouple subsystems and payloads from one another by placing them on different modules and, in doing so, provide the opportunity to collectively share subsystem resources amongst modules. This attribute is purported to yield unprecedented flexibility and survivability at the system level; something of great value to military decision makers. However, since current program planning tools have evolved to compare competing monolithic architectures, they fail to value new benefits offered by fractionation. In part to demonstrate these new value related attributes, the fractionated spacecraft concept is presently being explored in detail by DARPA through the F6 (Future, Fast, Flexible, Fractionated, Free-Flying) spacecraft program. The F6 program has the long-term objective of demonstrating that monolithic spacecraft can effectively be replaced by a set of smaller spacecraft modules (*i.e.*, a fractionated spacecraft). Large-scale implementation of the DARPA F6 program, and fractionated spacecraft more generally, would constitute a large shift in the design, development, deployment, and operation of government spacecraft.[3-5]

As an example of the implementation challenges facing ORS architectures, this paper examines the issues of implementing fractionated spacecraft in three primary sections. First, context is provided to the issue of military innovation of space systems by discussing relevant organizations and practices in the DoD science and technology enterprise as well the formal DoD acquisitions process. Second, eighteen implementation challenges for fractionated spacecraft are enumerated across technological, organizational, economic, and political domains. Third, a set of strategies are proposed for overcoming several of these implementation challenges. The paper concludes with a discussion on the criticality of evaluating fractionation and addressing interactions among domains.

CONTEXT: INNOVATION IN THE DOD ENTERPRISE

The issue of how innovation is managed and directed in military organizations has been a subject of inquiry for many years.[1, 2, 6-10] In one of the earliest essays on the topic, Morison,[7] a historian, examined the introduction of continuous-aim firing in the U.S. Navy, noting that despite demonstrated improvements in accuracy by 3000% over six years, widespread adoption was not even initiated until five years of effort by a determined Navy lieutenant and the solicitation of a directive from then President Roosevelt. This tale of the challenges of transition in military organizations has since been investigated through several seminal studies. For example, Sapolsky[9] argues that innovation is catalyzed through inter-service rivalry. Based on an analysis of the Polaris missile system development, Sapolsky cites the desire to secure providence over contested mission types (*e.g.*, versus the Air Force Minuteman missile system), as a necessary factor in overcoming the organizational inertia to maintain the status quo. In a similar vein, Rosen[9] identifies intra-service rivalry, and the presence of internal sub-cultures, as a key catalysts of change; Posen[8] argues that the catalyst must be external to the military organization, pointing to the influence of civilian leadership. Taking a different perspective, Lock-Pullan[10] argues that the extent to which a particular service will be receptive to innovation depends on their culture. For example, the USAF is smitten by technology, particularly flying machines. However, if the innovation does not align well with the particular organizational culture, the culture must change first.[11]

This common thread of conservatism in military organizations is reinforced by the current DoD acquisition system. While the two-tiered organizational structure nominally enables both (1) technology "push" in the form of broadly applicable basic research and development and (2) technology "pull" in the form of formal acquisition programs designed to close pre-defined capability gaps; in practice, formal acquisition programs receive disproportional support. Initial technology development within DoD is conducted by the Service Laboratories (*e.g.*, Air Force Research Laboratory, Naval Research Laboratory, and Army Research Laboratory) and several science and technology (S&T) organizations such as the Air Force Office of Scientific Research, the Office of Naval Research, and the Defense Advanced Research Projects Agency. These latter S&T organizations are focused primarily on a research-level investigation of basic physics and phenomenology. As these S&T organizations demonstrate concept feasibility, technologies are transferred to the Service Laboratories for further development, maturation, and demonstration of capability.

Once these innovation organizations mature concepts to the point where they can be realistically assessed for cost, schedule, and performance contributions to a given set of program requirements, they may be considered as part 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 assesses all available alternatives for meeting a validated warfighting need. Created to replace service-specific requirements generation systems, JCIDS is driven by the needs of U.S. Combatant Commanders with an emphasis on interoperability. JCIDS integrates the preferences of multiple stakeholders in the defense establishment by examining (perceived) capability shortfalls or gaps of the Combatant Commanders or Secretary of Defense. Then, the Joint Requirements Oversight Council (JROC) and Functional Control Boards (FCB) vet the requests—considering their validity as well as the possibility for addressing shortfalls with materiel (physical system) and non-materiel solutions (*e.g.*, new procedure, training). The three primary analysis steps in this capability-based analysis are:

1. Functional Area Analysis (FAA): identify operations, conditions, and standards needed to accomplish objectives
2. Functional Needs Analysis (FNA): assess ability to meet objectives given future and planned systems
3. Functional Solutions Analysis (FSA): selection of systems that best address capability gaps

In practice, "push" technology efforts and "pull" technology efforts are each integrated differently within the JCIDS bureaucracy. By definition, technology pull initiatives are near-term needs that existing programs have in order to satisfy warfighter objectives. This may entail any effort that can positively impact the program's cost, schedule or performance goals. As a result, the technology pull efforts tend to be focused very narrowly on a concrete, near- to mid-term technology need that a specific program office has on one of its systems. Many times this type of effort is called "applied" technology.

In contrast to "pull" technology, technology push efforts are characterized as "advanced" within the DoD enterprise and are not well-aligned with the JCIDS acquisition model. Push technology represent innovations or advances that may not have any immediately known applicability, but serve to (1) advance the state-of-the-art, (2) provide a path forward to solve long-term technical challenges, and (3) give rise to new strategic measures of effectiveness. As noted in Brown, Long et al.,[12] fractionated spacecraft fall under the "push" technology heading given the radically disruptive nature of the innovation and the wide range of potential applications and value propositions for DoD:

- Diversification of launch risk.
- Diversification of on-orbit failure risk due to uncertainties in operational environment, exogenous threats to the system, and flight hardware and software performance.
- Reliability enhancement through emergent sharing of subsystem resources and on-orbit redundancy.
- Scalability in response to service demand fluctuations and need for new applications and functionality.
- Upgradeability in response to technological obsolescence.
- Incremental deployment of capability to orbit (*i.e.*, staged deployment).
- Graceful degradation of on-orbit capability.
- Robustness in response to development delays, funding fluctuations, changes in requirements, and programmatic issues.
- Reduced integration, assembly, and testing time due to spacecraft subsystem decoupling.
- A reduction in the risk (*i.e.*, variability) associated with lifecycle costs.
- Production learning across multiple similar modules.
- Enabling spacecraft to be launched on smaller launch vehicles with shorter lead times.

It is worth noting that none of these purported benefits explicitly address traditional performance metrics associated with innovation.

IMPLEMENTATION CHALLENGES FOR FRACTIONATED SPACECRAFT

Although many of the potential benefits of fractionated spacecraft, and responsive space in general, address critical issues at the core of national security space policy, there are a diverse set of challenges that fractionated systems have faced, and will continue to face, on the journey from the DARPA F6 program to an operational capability. This section develops a taxonomy of challenges which are enumerated in Table 1. The vertical dimension enumerates four domains of study: technological, organizational, economic and political. The horizontal dimension identifies three categories of barriers: issues relating to appropriations of funds, sources of inertia that must be overcome in the acquisition process, and the feasibility of fractionation. Challenges are identified at the intersection of these dimensions; however, this section is structured in terms of the horizontal dimension: categories of barriers.

Appropriations

The first category of implementation challenges relate to the mechanism through which funding is allocated for space projects. In order to ensure accountability among public appropriations, rigorous valuation techniques are employed. However, since many of the benefits of fractionation act on emergent system properties (*e.g.*, flexibility, robustness) and result from radical innovation, they are undervalued by traditional measures of effectiveness. This section illustrates the organizational, economic and political aspects of the broader appropriations challenge: (1) the JCIDS acquisition framework of DoD emphasizes convention rather than innovation, (2) diffuse benefits and concentrated costs, (3) shifting from a cost-centric to a value-centric design approach, (4) unwillingness of the U.S. government to self-insure, and (5) competing national space program priorities.

(1) In terms of organization, the DoD JCIDS process of initiating acquisition programs favors technology "pull" rather than the technology "push" initiatives to which fractionated space architectures belong. In order for a need to be addressed in the JCIDS acquisition framework, it must originate from the Secretary of Defense or a warfighting commander who has identified an effect that he or she needs to create in the battle-space in order to meet wartime objectives. Given that fractionation provides efficiencies to (mostly) existing space capabilities—and that space (to date) is not part of a battle-space but rather a medium consisting of supporting services to the warfighter—fractionated satellite designs are unlikely to be specified by or known to a warfighter. Furthermore, given that subsequent steps in the JCIDS process (*i.e.*, FAA, FNA, and FSA) require a capability gap to be identified; architectural approaches which purport to better provide existing capabilities are likely to be underrepresented in JCIDS.

(2) While numerous government and commercial organizations may benefit from fractionation once the

Table 1 - Taxonomy of Challenges to Implementing Fractionated Spacecraft

	Appropriations	Inertia	Feasibility
Technological		**(6)** product platforming	**(12)** ability to support inter-module subsystem resource sharing via wireless transmission **(13)** module capability to maintain on-orbit relative positioning **(14)** module addition, replacement, and graceful degradation **(15)** launch and orbit insertion logistics
Organizational	**(1)** the JCIDS acquisition framework of DoD emphasizes convention rather than innovation	**(7)** government system program offices have become entrenched in an incremental evolutionary philosophy **(8)** an inability of established firms to accommodate disruptive innovation **(9)** the lack of a market in the DoD enterprise to serve as a corrective mechanism against entrenched firms	**(16)** current production and launch site management practices do not support a fractionated architecture approach
Economic	**(2)** diffuse benefits and concentrated costs **(3)** shifting from a cost-centric to a value-centric design approach	**(10)** the economic stake of satellite contractors in the status quo	**(17)** economies-of-scale reasoning by the DoD space acquisition establishment
Political	**(4)** unwillingness of the U.S. government to self-insure **(5)** competing national space program priorities	**(11)** the "back-to-basics" approach of DoD acquisitions	**(18)** geopolitical realities which manifest in less funding for advanced space technology

technology required for them is developed and space-qualified, it is unclear if any particular DoD organizations will be willing to take such concentrated risks when the benefits are so diffusely distributed. Therefore, fractionated architectures face a classic collective action problem.

(3) Fractionated spacecraft are often not perceived as beneficial or valuable systems relative to monolithic spacecraft – however, this is primarily a function of the design methodology paradigm used to evaluate the benefit, value, and costs of fractionated spacecraft.

Value-centric design methodologies (*e.g.*, Dynamic Multi-Attribute Tradespace Exploration)[13] quantitatively evaluate systems based on their benefit and/or value as perceived by the stakeholder(s) of the system – something not done by cost-centric design methodologies. As a result, value-centric design methodologies offer a promising solution for assessing systems (*e.g.*, fractionated spacecraft) that provide benefit and value via elements of a system design not captured by traditional measures of effectiveness (*e.g.*, cost). Therefore, a transition from a cost-centric to value-centric design methodology paradigm within government and industry is imperative to understanding and justifying the fractionated spacecraft concept.[5, 14]

(4) One fundamental advantage offered by fractionation—the diversification of launch and on-orbit failure risk—does not resonate with the U.S. government practice of investing enormous sums in reliability and mission assurance, rather than insuring launches.

(5) National priorities for the U.S. space program have predominantly led to the development of space system architectures tailored to missions that cannot be achieved by fractionated spacecraft (as fractionated spacecraft are defined and discussed herein).[15] One instantiation of this is the present focus and subsequent allocation of the majority of NASA's funding to The Constellation Systems program, the International Space Station, and the Space Shuttle as the result of former President George W. Bush's "Vision for U.S. Space Exploration."[16] It is therefore increasingly difficult to foster (and fund) new, innovative spacecraft architectures such as fractionated spacecraft in light of national space program priorities that do not align well with the objectives of such spacecraft architectures. Although programs, such as the DARPA F6 program, provide some evidence of government/national interest in fractionation, it will likely require a better matching of national space program priorities with the objectives and attributes of fractionated spacecraft for them to become a valuable and accepted alternative to monolithic spacecraft.

Inertia

By definition, radical innovations destroy the competence of incumbent institutions whose market position is tied to the status quo. This drives established firms to resist changes that do not align well with their core competences. In the space market, the status quo is reinforced through a number of mechanisms: (6) resistance to product platforming, (7) the fact that government system program offices have become entrenched in an evolutionary philosophy, (8) an inability of established firms to accommodate disruptive innovation, (9) the lack of a market in the DoD enterprise to serve as a corrective mechanism against entrenched firms, (10) the economic stake of satellite contractors in the status quo, and (11) the "back-to-basics" approach of DoD acquisitions.

(6) One of the inherent benefits and limitations of fractionated spacecraft is product platforming – that is, of course, assuming that platforming is used in fractionated spacecraft. Within the context of (fractionated) spacecraft, product platforming describes the use of standardized components for one or more hardware constituents of the spacecraft. One example of a product platform, for fractionated spacecraft, is a standardized module (*i.e.*, a platform) for power generation which can be used for several fractionated spacecraft, each of which may perform different missions. Product platforms provide the intrinsic advantage of not having to design and build spacecraft hardware elements from scratch (*i.e.*, "reinventing the wheel"), which is why product platforms are used to at least some extent in every spacecraft. However, one limitation of product platforms is that their ability to be integrated with multiple systems leads them to be sub-optimal for each system that employs them.[17] Another disadvantage of product platforms is the need for platform interface consistency and quality. Given that product platforms can be used for multiple systems, it requires that the platforms have consistent interfaces of a certain quality such that each system intending on using the platforms will be able to successfully "connect" to the platforms with limited difficulty. The interfacing issue illustrates an important challenge with product platforming, which is the need to balance the (i) consistency and quality of a platform's interfaces; (ii) its level of usability with current and future systems; and (iii) those systems' associated level of complexity as required for interfacing with the platform.

(7) Government space system program offices (and acquisition agencies more broadly) have evolved to a state of organization that does not accommodate

disruptive innovation. The monolithic spacecraft has emerged as the dominant design of national security space missions.[18] Organizationally, this manifests in system program offices that are not amenable to disruptive innovation. System program offices often prefer to baseline requirements of future systems from proven legacy designs. Such practices involve source selection and requirements specification activities that are unwilling to accept product attributes that are any less than previous designs, limiting the ability to consider new strategic measures of effectiveness. This practice of incremental evolutionary product development is exacerbated by three trends: (i) a system program office's pursuit of funding stability from Congress that encourages satellite architecture stability with an ability to deliver an assured capability, (ii) the reduction of government technical oversight in acquisitions[19] which make program managers dependent on prime contractors for the specification and evaluation of future system requirements, and (iii) an extremely risk-averse approach to satellite design and operation (where risk aversion leads to costly mission assurance practices, driving up costs, increasing downside risks, and feeding back into even higher levels of risk aversion).[20]

(8) "The essence of an architectural innovation is the reconfiguration of an established system to link together existing components in a new way."[21] Architectural innovations by established firms subscribing to agreed-upon measures of effectiveness of a dominant design (*e.g.*, cost-per function in monolithic satellite paradigm) are constrained by formal organizational practices and structures.[22] Because the monolithic approach constitutes a core competency of the system program offices, prime contractors, and supply networks of the U.S. space establishment, it is very challenging to implement a major innovation such as fractionation.

(9) The relative lack of competition in the DoD market for space systems reduces the potential for "disruptive" market corrections. In particular, the work of Christensen[23] has shown that outstanding commercial firms may lose market share to innovative start-up firms because of a failure to recognize the need to abandon traditional business practices. While competitive commercial markets generally have this corrective mechanism, no such corrective mechanism exists in the government space enterprise. This lack of a market mechanism in U.S. government space acquisitions to correct the march towards longer design lives, higher reliability, and more capable yet fewer space systems cause the U.S. space architecture to be locked into a dominant design of the established paradigm. Figure 1 provides a notional illustration of this trend in terms of the pressures for product integration and "dis-integration". It may be argued that the current architectural approach is stuck in a box of "organizational rigidities" in the integrated helix on the left. Without many "niche competitors" in the DoD space acquisition enterprise, it is only "high-dimensional complexity" that may drive "pressure to dis-integrate."

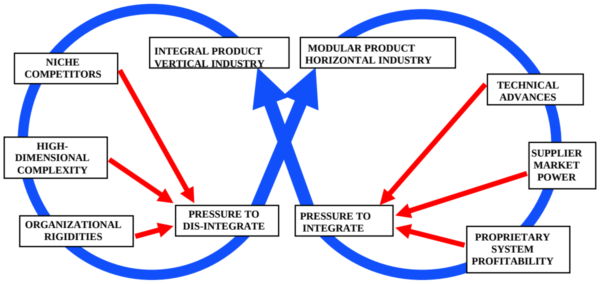

Figure 1. The Double Helix: The Dynamics of Product Architecture and Industry Structure*

(10) Existing satellite prime contractors have a large stake in the status quo. For example, given the high non-recurring costs associated with developing and assuring the reliability of satellite platforms, what economic incentive is there for fractionation? The general economic problem here is that there are organizations in positions of power with a concentrated interest in maintaining the status quo.

(11) Recent space programs (*e.g.*, NPOESS, SBIRS-Hi) have tarnished the reputation of the national security space establishment to deliver promised capability on time and within budget. In response, the "back-to-basics" emphasizes keeping technology development in the S&T portion of the budget and out of formal acquisitions programs. Since most funding is directed at formal acquisitions programs, this policy may limit funding for fractionation.

Feasibility

The final category of implementation challenges relate to the feasibility of fractionated spacecraft with regard to transitioning from an innovative spacecraft concept to a viable, fully-operational system. From a technical point of view, four key enabling technologies must reach maturity before implementation becomes feasible: (12) an ability to support inter-module subsystem resource sharing via wireless transmission,

* Christensen "The Drivers of Vertical Disintegration" HBS working paper, Oct 1994 and Fine & Whitney, "Is the Make/Buy Decision a Core Competence?" MIT Working Paper, March 1995.

(13) module capability to maintain on-orbit relative positioning, (14) module addition, replacement, and graceful degradation, and (15) launch and orbit insertion logistics. There are also organizational, economic, and political challenges associated with the feasibility of fractionated spacecraft which include: (16) current production and launch site management practices do not support a fractionated architecture approach, (17) economies-of-scale reasoning by the DoD space acquisition establishment, and (18) geopolitical realities which manifest in less funding for advanced space technology.

(12) Fractionated spacecraft physically separate subsystems and payloads by placing them on different modules and, in doing so, share some of the subsystem resources amongst modules (*e.g.*, power, communications, processing, attitude and guidance determination).† Through the dispersion and subsequent sharing of fractionatable subsystems, there are associated interfaces required on the modules that rely on shared resources and/or share their resources.[3] These interfaces may be simple instantiations of current technology, as is in the case of wireless information transmission where the associated interface would be a simple omni-antenna on modules. However, in a few particular instances—most notably when the power subsystem is shared—developing the interfaces associated with the sharing of a subsystem without adversely affecting the modules that supply the shared resource provides a daunting technical challenge.

(13) Transitioning from monolithic to fractionated spacecraft changes the on-orbit concept of operations (CONOPS). In the case of fractionated spacecraft, the CONOPS must address the need to maintain a formation/cluster flight pattern with the modules—an especially critical challenge as the on-orbit separation distance between the modules approaches the accuracy tolerance of the guidance determination system. To successfully maintain a flight pattern, it is both necessary to identify the state variables (*e.g.*, position, velocity, and acceleration) for each of the spacecraft modules such that their relative states to one another and Earth are known, and to have an active attitude control and propulsion system to make on-orbit corrections to each modules' respective state as needed. One proposed approach for determining the state variables is to use an Autonomous Relative Navigation (ARN) system on each module which would interact (via a visual positioning system) with a "central module" in the cluster such that the state variables for all modules are determined by that central module.[24] As the potentially catastrophic danger of on-orbit collision must be constantly avoided, it is ultimately the interdependency of having to both accurately determine and correct the modules' state variables that increases the difficulty associated with CONOPS for fractionated spacecraft.

(14) Fractionated spacecraft are operationally responsive because they have the ability to add and replace new or existing modules in their respective on-orbit cluster during their lifetime. This ability, from which much of the benefit of fractionation is derived, provides the fourth technological challenge of fractionation: being capable of on-orbit module addition, replacement and graceful degradation. With the need to dynamically adapt and evolve a fractionated spacecraft, such issues as to how to effectively integrate new modules on orbit while removing others (module replacement and graceful degradation), or integrating new modules without removing others (module addition), while still maintaining a particular level of service delivery and avoiding on-orbit collision becomes increasingly difficult.[25]

(15) In terms of launch vehicle procurement and launch site preparations, fractionated spacecraft pose the challenge of having to coordinate launch vehicles and launch site operations, provided that more than one launch vehicle is required to launch all of the modules. A probable future scenario is the inability to launch all of a fractionated spacecraft's respective modules from the same site and/or at the same time. This scenario is particularly relevant given the lack of small payload, low-cost launch vehicles in the Unites States (although this may change with the development of the Falcon I and Ie by SpaceX). Additionally, there exists the challenge of inserting the fractionated spacecraft modules on-orbit from the launch vehicle(s),[25] which becomes difficult in the likely case where there are inter-module operational dependencies (as would be the case if resources are shared). This challenge is further exacerbated by the launch vehicle coordination issue in the case where multiple launch vehicles are needed to launch the fractionated spacecraft's modules.

(16) There are organizational challenges associated with manufacturing a fractionated spacecraft and using more than one launch vehicle to launch all of a fractionated spacecraft's modules. Due to the inherent modularity of fractionated spacecraft (*i.e.* the physically separated nature of the spacecraft's constituents) it is likely that there may be an increase in the number of facilities manufacturing a fractionated spacecraft's

† It should be noted that not all spacecraft subsystems are "fractionatable." Some subsystems, such as the thermal control system, must be present in all modules of a fractionated spacecraft.

subsystems and modules. This gives rise to several organizational challenges not seen (or seen to a lesser degree) with monolithic spacecraft. These challenges may include: (i) the need to manage a (geographically) dispersed workforce; (ii) subsystem and module interface consistency and quality control; (iii) implementing standardized, manufacturing quality assurance and inspection programs across multiple manufacturing facilities; (iv) a change in the protocol for integration, assembly, and testing processes; and (v) the need for a robust managerial approach to address program-related issues. Launching a fractionated spacecraft may also create several organizational challenges which include: (i) procurement of more than one launch vehicle, coordinating launch schedules, and accounting for the possibility of launch slips; (ii) coordination of pre-launch and launch site operations for multiple launch venues; and (iii) the build-to-order production approach of launch vehicle manufacturers.[26] In many instances with regard to the production and launch of fractionated spacecraft, it is clear that implementation practices of present spacecraft programs are not fully ready to support fractionated spacecraft.

The last two feasibility challenges are economic and political concerns, respectively.

(17) Advancements in space technology and economies-of-scale reasoning have increasingly driven DoD to concentrate capability on fewer and fewer space assets. This argument is based on the high cost of escaping the Earth's gravity well and the proportionately higher cost per unit mass associated with launching small spacecraft.

(18) Geopolitical realities (*e.g.*, Iraq, War on Terrorism, lack of technological peer competitor in space) have caused U.S. space activities to (i) lose some of their Cold War-era importance as a strategic medium for international prestige, and (ii) shifted national attention to other priorities (*e.g.*, economic competiveness in globalized economy). Therefore, Congress may focus more on sustaining space capabilities than on developing new technologies. It will be hard to implement a radical innovation such as fractionation without a clear business case (*e.g.*, "flagship" mission enabled by fractionation) or a disruptive event (*e.g.*, "Pearl Harbor" in space).

STRATEGIES FOR OVERCOMING IMPLEMENTATION CHALLENGES

Given the enumerated challenges within the current context of DoD innovation, several preliminary strategies for overcoming the challenges are proposed. This section is organized using the same three categories – of Appropriations, Inertia, and Feasibility – as in the preceding section. A summary of strategies for overcoming each of these categories is provided in Table 2.

Table 2 - Summary of Proposed Strategies

Appropriations	Inertia	Feasibility
Precisely define value proposition and leverage emerging valuation techniques	Incentivize paradigm shift	Support for maturing enabling technologies

Value System Properties

This paper has reiterated several times that although fractionated spacecraft (and responsive space more generally) have the potential to vastly improve the flexibility and survivability of space systems, these attributes are often underrepresented in traditional assessment methodologies (challenges 1-5). To begin to overcome this category of challenges, two strategies are proposed.

<u>Precisely Define Value Proposition</u>

Even if we are able to mature the underlying technologies of fractionation and conduct a successful on-orbit demonstration, the lesson of DARPA's experience with the Orbital Express on-orbit servicing program is that such success does not translate to an operational capability (and certainly not a dominant element of spacecraft design) without a rigorous value proposition for the intended users. Three ideas are proposed to define the value proposition for fractionation:

1. Conduct research into historical failures of the monolithic paradigm to evaluate the benefits of a fractionated approach. Equal emphasis should be placed on examining both the *benefits* and *costs* of fractionated and monolithic architectures. For example, an analytic evaluation of the dangers of concentrating capability on very few assets[27] and of the benefits of distribution and diversity in space architecture[28] might sway senior decision makers to consider fractionation as a serious competitor to monolithic approaches.
2. Rigorously investigate the advantages provided by fractionation for the survivability of government space systems. As embodied in the Milstar protected communications satellite constellation, the government is willing to spend premium dollars for assured access to space capabilities. Therefore, DARPA's F6 program might evaluate the consequences *in terms of survivability* of alternative future U.S.

national security space architectures. Preliminary insights might also be derived from examining the reasons why the Strategic Defense Initiative embraced the distributed Brilliant Pebbles architecture as the only survivable and cost-effective space-based missile defense system. The Iridium satellite communications system provides an operational example of a system in which the survivability of the communications service is achieved not by the individual satellites but by the overall network architecture. Iridium survivability features include dynamic control and routing of satellite crosslink's around unavailable nodes, on-orbit satellite spares, and the ability to control all 66 operational spacecraft from a single ground facility. For example, following the shattering of a satellite on February 10, 2009, Iridium was able to move one of its in-orbit spares into the network constellation within a month.[29] "…[T]he design philosophy provides redundancy at the system level instead of the hardware configuration level. Autonomous operation and dynamic resource management and routing provide constellation failure mitigation. In effect, the traditional hardware redundancy is spread over many spacecraft."[30]

The DARPA F6 program and other programs with the objective of justifying the fractionated spacecraft concept should sharpen the purported benefits of fractionation when making its business case. To accomplish this, these programs should begin to adopt (or continue to use) a value-centric design philosophy for comparing and contrasting the benefit and value offered by both monolithic and fractionated spacecraft. Furthermore, these programs should increase stakeholder confidence with value-centric spacecraft design approaches by benchmarking them against current, trusted cost-centric design methodologies. However, even with the adoption of value-centric design philosophies, there may be other contributing factors required to sharpen the purported benefits of fractionation when making a business case. For example, even if diffuse benefits arise from investment in an infrastructure capability (as embodied in the eighteen advantages of fractionation enumerated in the F6 broad area announcement), one lesson to be learned from on-orbit servicing is the need for a "flagship" mission and a direct beneficiary of the initial technology deployment. Thus, it may be necessary to identify and have such a flagship mission when creating a business case for fractionated spacecraft.

Incorporate "-ilities" into JCIDS Acquisition Framework

The business case for fractionation, and ORS more generally, is indicative of the systems engineering challenge of incorporating "-ilities" into conceptual design. Given that non-traditional design criteria—such as flexibility and robustness, collectively referred to as "-ilities"—are increasingly regarded as critical system properties for delivering stakeholder value,[31, 32] ongoing systems engineering research has established descriptive taxonomies and prescriptive methods for the incorporation of the "-ilities" in system design.[13, 33-39] The "-ilities" may be defined as temporal system properties that specify the degree to which systems are able to maintain or even improve function in the presence of change. The "-ilities" explicitly recognize that, in addition to meeting requirements in a static context, the performance of system architectures is defined by an ability to deliver value to stakeholders in the presence of changing operational environments, economic markets, and technological developments [34]. According to Dr. Marvin Sambur, former Assistant Secretary of the Air Force for Acquisitions[31], a generalized new definition for robustness applied to military acquisitions means developing systems that are:

- capable of *adapting* to changes in mission and requirements
- *expandable/scalable*, and designed to accommodate growth in capability
- able to *reliably* function given changes in threats and environment
- effectively/affordably *sustainable* over their lifecycle
- developed using products designed for use in various *platforms* and systems
- easily *modified* to leverage new technologies

The performance of fractionated spacecraft, and ORS more generally, is high in terms of the "-ilities". Therefore, for JCIDS to value the benefits of ORS, it must be (1) amenable to technology "push" programs that efficiently meet warfighting needs and (2) structured to recognize the benefits of the "-ilities" such that fractionated architectures may be approved as major acquisition programs. To address the challenge of technology push, new avenues in initiating JCIDS should be established such that both warfighting commanders' needs are addressed as well as the long-term interests of supporting the warfighter with an efficient supporting infrastructure.

As currently structured, when a validated warfighter need is added to the JCIDS process, a High

Performance Team (HPT) is convened. This team contains representation from the warfighter, the supporting service operational community (the user), the acquisition community, the test community, and the maintenance/sustainability communities. Using this approach provides for a rapid method of integrating multiple, and sometimes divergent, stakeholder requirements into the system requirements specification. In this process, a rigorous system analysis framework should be utilized to ensure that an integrated lifecycle perspective is taken from the very start of the system development process. Such a lifecycle perspective, including a sensitivity analysis that accounts future uncertainties, will allow lifecycle cost-benefit trades to better evaluate fractionated architectures relative to monolithic architectures.

Incentivize Paradigm Shift

Military organizations are difficult to change, in part because there is much less pressure of displacement of incumbents by entrant firms compared to other industries; established firms do not feel pressure to deviate from the status quo because they are protected by extremely high barriers to entry (challenges 7-10). If change is to occur towards a responsive space paradigm, a fundamental shift in the governing acquisition philosophy will be required. Addressing this is an extremely complex problem and beyond the scope of this paper, however two ideas for how to redefine the product unit of acquisition are provided here.

Procure Satellite Service Instead of Programs

The current discussion between space acquisition agencies and Congressional funders takes place largely in the context of individual agency directorates. This program-based funding structure appeals to system program offices because they can specialize their Congressional liaison activities within the context of their individual program and appeals to Congress because deliverables are measurable and explicit—conducive to their oversight function. However, this program-based acquisition structure does not foster efficiency (or cooperation) among program offices in the space acquisition community. This structure also does not provide Congress an ability to effectively distribute limited resources among candidate programs given their limited resources for architectural decision-making.

An acquisitions paradigm in which funding is received from Congress for acquisitions agencies to procure services rather than programs might provide the managers of program offices incentives to invest in value-efficient architectures. If program managers have an ability to "keep what they save" rather than "lose what they don't spend," architectures which may offer long-term efficiency improvements (*e.g.,* fractionation) may gain traction. The key goal is to empower program offices to take a longer view than the annual budgetary cycle. A critical issue will be to build confidence with Congressional appropriators who don't want to lose oversight leverage. The threat of reduced funding for a particular satellite service in the event of unresponsiveness to Congressional priorities may mitigate these concerns.

Acquire Satellite Payloads Independently of Supporting Bus Infrastructure

As enterprise architectures in industry evolve to structures representative of the technical architecture (*e.g.*, decomposition of work team based on product modules), it is essential that future government organizational structures for the procurement and management of fractionated architectures are not constrained by legacy constraints. In other words, the current structure of system program offices should not be conserved in a fractionated acquisitions paradigm. Rather, one large organization should be developed to support infrastructure modules (*e.g.*, power generation and storage) while the existing system program offices should transition to the exclusive procurement of payload modules. This revised organizational structure is essential to capitalize on the economies-of-scale of infrastructure commonality across military mission areas. Implementation of this paradigm will require extensive specification of standards and convergence among government stakeholders. Attempts to achieve convergence for the TACSAT program offer a host of lessons in this area.[40]

Mature Enabling Technologies

Several key enabling technologies must be matured before fractionated spacecraft become feasible. This work is currently being conducted through a number of academic and government research organization collaborations. Specifically, the continued support of DARPA's Falcon[‡] and System F6[§] programs may help to mature these underlying technologies. Additionally, work presently being conducted at the Massachusetts Institute of Technology and the University of Maryland on the development of ARN systems is greatly increasing the potential for fractionated spacecraft modules to maintain formation/cluster flight patterns on-orbit.[24, 25, 41] Furthermore, the University

‡ http://www.darpa.mil/tto/programs/Falcon.htm
§ http://www.darpa.mil/TTO/solicit/BAA07-31/Dr._Owen_Brown's_Brief.pdf

Nanosatellite Program (UNP), lead by Air Force Research Laboratory, has been a continual contributor in the development of technology required for the sharing of subsystem resources amongst the modules of a fractionated spacecraft via wireless transmission.[42] However, as budgets become further constrained and given current geopolitical realities (challenges 11 and 18), securing the funding required to ensure future enabling technologies are developed is imperative.

CONCLUSION

Given the growth of military dependency on space systems and the dynamic nature of user requirements, operationally responsive space, as illustrated through the case of fractionated spacecraft, may offer a compelling value proposition to the national security space community. However, with fractionated spacecraft perceived as a radical innovation having diffuse benefits and concentrated costs, successful implementation requires overcoming several challenges. While this paper does not purport to offer a complete set of solutions, the presented taxonomy of challenges adds structure to the problem in three important ways. First, it illustrates the extent to which key challenges are not only technical but also organizational, economic, and political. Second, the paper recognizes that challenges in each of these domains are interdependent.[43] While technology is a prerequisite to an operational capability, gathering political support through construction of a precise value proposition is a prerequisite to funding for the development of advanced technology and as well as to later transitioning that technology to an operational capability. Third, the paper emphasizes the need to consider the total product system supporting fractionation—including access to low-cost launch vehicles, a management enterprise structured to capitalize upon lifecycle efficiencies, and a supplier base converging on enabling standards.

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