

“STANDARD BUSES, MODULAR BUSES, AND PLUG-AND-PLAY BUSES; WHAT IS THE DIFFERENCE AND WHY DOES IT MATTER?”

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ABSTRACT

There is significant confusion in the space industry today over the terms used to describe satellite bus architectures. Terms such as “standard bus” (or “common bus”), “modular bus” and “plug-and-play bus” are often used with little understanding of what the terms actually mean, and even less understanding of what the differences in these space architectures mean. It may seem that these terms are subtle differentiators, but in reality these terms describe radically different ways to design, build, test, and operate satellites. Furthermore, these terms imply very different business models for the acquisition, operation, and sustainment of space systems. This paper will define and describe the difference between “standard buses”, “modular buses” and “plug-and-play buses”; giving examples of each kind with a cost/benefit discussion of each type.

1. INTRODUCTION

It must be recognized that a consumer of space products does not care what type of spacecraft bus was used to produce their product. The consumer cares only about the value proposition for that space product; that is, “what the consumer gets for the price he pays”. This can be thought of as the value of the product divided by the cost. This paper will assess the impact of the spacecraft bus architecture on the consumer’s value proposition for space products. This will be assessed by comparing the inherent ability of the three bus architectures (standard bus, modular bus, and plug-and-play bus) to increase the consumer’s value proposition thru either providing increased capability, reduced cost, or reduced development time. The three spacecraft bus architectures will be assessed against each of the following cost reduction strategies: economies of scale, the application of a learning curve, smoothing out the supply chain for parts, reducing parts inventory, and reducing complexity. The value of the space product is also influenced by the spacecraft bus architecture. The impact of the three spacecraft bus architectures on each of the following value improvement strategies will be assessed: increased flexibility to meet a wide range of

needs, rapid incorporation of new technologies, and decreased time to need.

This paper will provide a qualitative comparison of a standard bus, a modular bus, and a plug-and-play bus architecture to a consumer’s value proposition for space products. It will show that the development of a true plug-and-play capability for satellites will provide significant payoff; although the investment required to fully develop the enabling hardware and software will be significant.

2. DEFINITION OF BUS TYPES

The first task in eliminating confusion surrounding this topic is to define the terms being used. For the purposes of this paper the following definitions will be used (for an in-depth description of historical review of standard and modular bus development efforts see [1]):

- **Standard Bus:** A bus with a standard launch vehicle and payload interface that can be purchased *unaltered*. The expectation is that the bus can be purchased by the government and delivered to a systems integrator for integration with the payload and subsequent testing.
- **Customizable Bus:** A bus from a standard product line that is modified to meet specific mission needs. This category includes most of what industry today calls a standard bus.
- **Modular Bus:** A bus that is assembled from modular components with standard interfaces and minimal interdependencies between modules. In the early developmental states, extensive system integration and testing is required.
- **Plug-and-Play Bus:** A modular bus with open-standards and interfaces, self-describing components, and an auto-configuring system. System integration is simple and testing tasks are automated. There are two key differences between a Plug-and-Play satellite bus and spacecraft that

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have been previously developed. That is: 1.) the use of auto-configuring hardware and software interfaces between the modules, and 2.) these interface standards are described by Open-System Standards.

According to the US DoD Open-Systems Joint Task Force the definition of an open system is [2]:

A System That Employs Modular Design, Uses Widely Supported and Consensus Based Standards for its Key Interfaces, and Has Been Subjected to Successful Validation and Verification Tests to Ensure the conformity of component and interfaces to the standards.

Further, they define the key characteristics of an open-system as one that is :

- Based on publicly available specifications, preferably maintained as standards by internationally recognized governing groups
- Well-defined, widely used Non-Proprietary interfaces, services, formats
- Durable (stable or slowly evolving) Component Interfaces, that facilitate [rapid] component replacement and addition of new capabilities
- Upgradeable, Through incorporation of additional or more capable components With Minimal Impact on the system

With this definition we must also spend a minute to describe the type of “**key interfaces**” in a spacecraft bus. These are:

- Mechanical interfaces that describe volume, mass, physical connections and alignment
- Power interfaces that define current and voltage
- Data interfaces that describe data format, data throughput and logic
- Thermal interfaces that define heat transfer properties and allowed temperatures,
- Environmental interfaces – EMI, radiation, outgassing allowed

It is also useful to define the term **modular-design** or a **module**. This is a design approach based on dividing a system into smaller parts (or modules) that can be created independently and assembled together to achieve the performance required of the complete system. In general a modular design results in reduction in cost due to the ability to develop modules in parallel rather than one complex system developed in serial, and due to the ability to re-use the components in multiple combinations. Modular design is an attempt to combine the advantages of standardization (high volume normally equated with low manufacturing costs) with those of customization [3].

3. METHODS FOR INCREASING THE VALUE PROPOSITION

In “Economics of Strategy” the **value proposition** is defined as the sum total of benefits a customer receives in return for the customer's associated payment (or other value-transfer) [4]. In simple words the value proposition is what the customer gets for what the customer pays. That is:

$$\text{Value proposition} = \frac{\text{Customer benefit}}{\text{Cost}} \quad (1)$$

Thus to increase the value proposition for a product one must either reduce the cost of the product, add customer benefit, or both. So let us examine each of these variables in turn. The well known ways to reduce the cost of a product include:

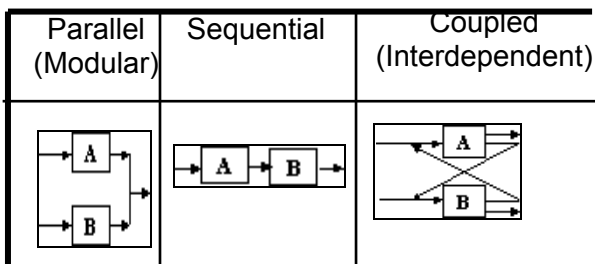
- Utilize economies of scale and scope to spread fixed costs over a greater number of units
- Application of a learning curve to reduce variable costs by doing the same thing repetitively
- Smooth the supply chain to lower vendor costs
- Reduce inventory costs
- Reduce or manage complexity in the system

There are several well known ways to add customer benefit (or customer value) to a product. The first way is to increase the flexibility (scope or number of potential applications) of the product. This allows the product to meet a wider variety of the customer's needs. Flexibility allows the customer to utilize the product to respond to uncertainty or changes in threats or opportunities. Another way to add value to a product is by increasing the number of modules which in turn increases the options to incorporate new innovations. This is simplified in a modular architecture because the interdependencies between components are decoupled, permitting innovation at the module level. This decoupling enables development to take place in parallel at the module level. This provides differentiation to the producer of a product in a tight market-place and allows that producer to reduce time to market for new capabilities [5]. According to Clark and Baldwin [3], the value of adding modules (or splitting) a system is proportional to the square root of the number of modules. Thus the option value of a system with 25 modules has 5 times the value of an unitary system. It is clear that one powerful method to increase the value proposition of a complex system like a spacecraft bus is thru the use of modular-design practices.

4. COMPLEXITY: THEORY OF DESIGN

When assessing acquisition models for complex systems it is useful to review the Design Structure Matrix method [8]. Complexity in these systems is often viewed as an obstacle to the design and development of innovative products. However, complexity in systems enables more capability and facilitates innovations that would not be possible otherwise. Therefore complexity management becomes critically important to achieving product development goals. The Design Structure Matrix is one approach developed to manage the design and optimization of complex technical systems.

In the Design Structure Matrix method there are three types of dependencies between activities or system elements A and B within complex systems. (1) Parallel or modular: in this case A is independent of B and no information exchange is required between the development of the two system elements. (2) Sequential: in this case A influences B. A must be completed before B. (3) Coupled or interdependent: in this case A influences B and vice versa. Resolving this interdependency requires an iterative design process of trades and analyses. These dependencies are represented with the following schematic:



The trend in Design Complexity from the least complex process to the most complex process from a technical, management, and organizational view is:

- independent parallel system elements
- sequential elements
- Coupled elements within a component
 - o These dependencies can be solved by an individual or informal working group
- Coupled elements that span multiple components
 - o These dependencies must be solved with systems engineering working groups
- Coupled elements that span multiple departments within an organization
 - o These dependencies require inter-departmental coordination, often resulting in multiple meetings, rivalries and turf-wars

- Coupled elements that span multiple companies
 - o These dependencies require inter-company coordination resulting in high transaction and agency costs, contracts, SOW's, ICD's, travel, etc..
- Coupled elements that span multiple governmental organizations
 - o These dependencies require negotiated approvals, coordination and compromise of system goals, funding coordination, alignment of stakeholders

It is clear that spacecraft development today falls into the most complex case specified above. That is development of the spacecraft system span multiple companies and multiple government organizations. This results in a lengthy requirement generation processes, lengthy and costly design, development and testing processes, significant management burden, and ultimately compromises that lead to dissatisfaction by the users of the system.

The Theory of Design Complexity shows that by incorporating a modular-design process applied to spacecraft development and acquisition decouples many design elements and results in simplified coordination of tasks and decision making. Modularity in the system allows for maximum re-use of components, and for parallel development [5, 6].

5. DO STANDARDS RESTRICT INNOVATION?

It is often claimed that "standardization prevents innovation". In fact this is far from reality. A study of four case histories in various domains - manufacturing, computer hardware, mechanical component design, and product data exchange reveals that... **innovation is often spurred - directly and indirectly - from standards** [7,8, 9].

Jorma Ollila, the Chairman of Nokia's Board of Directors reinforced this notion when he stated, "... Open standards and platforms create a foundation for success. They enable interoperability of technologies and **encourage innovativeness** and healthy competition, which in turn increases consumer choice and opens entirely new markets." [8] The EU Commissioner Erkki Liikanen also stated, "Open standards are important to help create interoperable and affordable solutions for everybody. They also **promote competition** by setting up a technical playing field that is level to all market players. This means lower costs for enterprises and, ultimately, the consumer."

It is clear that standardization and use of modular-design rules do not restrict competition and innovation. In fact, they are a key component to stimulating innovation.

6. COMPARISON OF SPACECRAFT BUS TYPES

In order to compare the value proposition of spacecraft bus types, the two types representing proposed approaches for building responsive space busses of the possibilities will be qualitatively compared. That is a Standard Bus and a Plug-and-Play Bus. The comparison will be based on a life-cycle of 20 years. It will be assumed that the technology life-cycle of the components in the spacecraft bus is 5 years.

6.1. Standard Bus Acquisition Approach

Several studies have found that spacecraft bus requirements for a large majority of responsive space missions can be encompassed with three basic bus designs: a spacecraft bus for high-precision pointing Low-Earth-Orbiting missions (LEO HPP); a spacecraft bus for medium precision pointing Highly Elliptical earth-Orbiting missions (HEO MPP); and a spacecraft bus with minimal pointing requirements but a high degree of maneuvering capability for LEO servicing and inspection missions. Thus it will be assumed that three separate spacecraft busses are required and sufficient to meet all mission requirements for a given customer. Assuming a technology obsolescence of five years, this means that six new spacecraft designs must be produced every 10 years. Thus over a 20 year life-cycle 12 new spacecraft would have to be redesigned for this customer. Further assuming that 50 satellites were purchased in the first decade (for a flight rate of 5 flights per year), this would imply that 8 missions were flown per each spacecraft bus design. If in the second decade 140 satellites were purchased, there would be roughly 23 missions per each spacecraft bus design. Given today's flight rates for spacecraft missions this would represent the best-case scenario for leveraging economies of scale.

If it is assumed that there is an 18 month lead time on components for spacecraft (as is the norm for critical spacecraft components today), then it is given that mission types and bus capabilities must be locked-in at the start of a 6.5 year period. At the beginning of this 6.5 year period the customer must also plan for the proper number of buses to support each mission type. That is X copies of bus A, Y copies of bus B, and Z copies of bus C. All of the nonrecurring costs and the inventory costs are incurred in the beginning of the 6.5 year period. There is also a strong potential for waste in

this model as the pre-selected quantity of buses A, B, and C may be in excess of the actual need, also requiring the development of additional buses of other needed types. Because of the lead time in procuring long lead hardware, and construction time, this creates a critical problem when there are not enough buses of a specific type to meet the needs of the customer.

This acquisition approach has negative impact on supply chain management. The supply chain has bursts of activity followed by long periods of inactivity. These bursts are driven by the 5 year technology obsolescence cycle and the desire to utilize economies of scale during production. In this acquisition model the component vendors must structure their organization for feast or famine. In addition the time horizon for return on component innovations is long and uncertain.

6.2. Modular PnP Bus Acquisition Approach

The PnP Bus Acquisition Model assumes that spacecraft are "modularized" and there is no one distinct spacecraft bus design. Rather, there are a bounded series of spacecraft modules or components that can be quickly integrated into a variety of combinations since a common spacecraft "architecture" is used for each combination. That is a common set of physical, electrical, thermal, and data standards are used for each spacecraft bus configuration and a common, reusable, modular flight software library is utilized. Spacecraft bus configurations can be pre-designed and tested prior to being needed and left as unassembled components. The spacecraft can then be assembled as needed. Economies of scope and learning-curve benefits still apply since the same common spacecraft "architecture" is used for each mission and components can be used for more than one specific mission type.

The PnP Bus Acquisition Model has significant impact on inventory management. First, it is likely that a wider range of components will be held in inventory than for a standard spacecraft bus acquisition model. For example, there may be multiple battery capacities in the PnP Acquisition Model since it is relatively trivial in this model to "customize" spacecraft bus performance simply by interchanging a spacecraft component. This would require a greater focus on logistics and inventory management. However, the benefit to this approach is that it would be possible to turnover the inventory more quickly and rapidly incorporate a new innovation in battery performance. In fact, in this approach the demand prediction horizon is moved from 6.5 years for a standard bus acquisition model (assuming 18 month component lead-times and a five-year bus life-cycle) to an 18 month lead time. So, in the PnP Bus Acquisition Model the customer must plan and inventory for 18

months of future years needs vice 6.5 years for a standard bus acquisition approach. This benefits the component suppliers, as they can structure their organization for continuous development and production. One final important factor for inventory management is that for the true PnP Bus Acquisition Model to be implemented system integration and testing must become trivial. At that point module-level testing is sufficient to guarantee performance of the spacecraft bus. Inventory management procedures must develop processes and procedures to ensure component level performance, health and reliability.

There is the potential for some waste in this acquisition model as there is in the standard bus acquisition model. However in this case the waste is driven by the length of the component lead-time (18 months) versus a 6.5 year block development time as for the standard bus acquisition model. So, as previously discussed, the developer has to predict only 18 months of demand vice 6.5 years of demand.

In the PnP Bus Acquisition Model new technologies can be incorporated into the system with minimal impact on the rest of the design (so long as the new technologies do not violate the specified component interface standards). Spacecraft bus designs can evolve in a continuous fashion to incorporate new technologies or mission needs. Perhaps the most important effect of moving to a PnP Bus Acquisition Model is to force maximum re-use of designs, hardware, and software. This has been proven in many high-volume industries such as personal computing and automobiles and in low-volume industries such as supercomputers, and high-performance interruptible power supplies to drastically reduce the cost of producing a new product and to drastically increase the differentiation of these products from it's competitors [5].

6.3.Comparison of Bus Acquisition Models

The comparison of these bus acquisition models is summarized in the following table:

Table 1. Comparison of Spacecraft Bus Acquisition Models

	Standard Bus	PnP
Fixed Costs	Moderate	High, dependent on cost of developing modular arch.
Variable Costs	Moderate	Moderate to Low
Economies of Scale	At bus level	At component level
Economies of Scope	Limited, because different buses and blocks will likely be built by different vendors.	High. Open system architecture used for multiple missions over a long time span.
Learning Curve	85% over each bus quantity	85% over 20 year total
Supply Chain	Lumpy	Smooth
Inventory Management	Build and store 5 yrs worth of buses to take advantage of economies of scale in manufacturing	Store 1.5 yrs of components required to meet range of mission requirements
Complexity	Low, controlled by specifying LV and PL I/Fs	Low, controlled by eliminating parameter and task interdependencies
Flexibility	Low	Moderate to High
Option Value	Low	High

7. MODULARIZING IS EXPENSIVE

The previous analysis of spacecraft bus acquisition models presents a compelling case for the development of a modular, open-systems "plug-and-play" capable spacecraft bus architecture. It is often argued that if this business model were so compelling the industry would have adopted it in the late 1970's when the technologies first became available in the high-performance computing world. However, as we know today that did not happen. Why?

Ultimately "modularizing" a complex system is costly. It is costly in two important ways: (1) the capital costs required to develop, validate, and implementation, and (2) in cultural costs. Let's take each of these costs in order. First, an example from history highlights these costs. In the early

1960's the computing industry looked very much like the spacecraft market does today. That is, nearly every computer at the time was unique and was built one at a time from components that were highly coupled and interdependent. In addition, the market was quite small and driven primarily by the U.S. Government. At that time IBM engineers recognized there would be substantial benefit to "modularizing" their mainframe computer design. It is estimated that IBM spent over \$2.5B in R&D and over \$20B total to develop the IBM System/360 (cost figures in 2006 dollars). This far exceeded the initial estimate to modularize the mainframe architecture. However, it is estimated that in 1970 the market value of the IBM System/360 exceeded \$190B.

Secondly, "modularizing" a complex system has significant human capital cost and is in fact counter to the way design of complex systems is handled in most companies and industries today. As described in Section 4 above, complex systems with **coupled elements that span multiple components** dependencies must be solved with systems engineering working groups. Typically these working groups are assigned to individual managers to oversee. These managers are required to trade risk against schedule and resources to achieve the goals of their specific working group. Therefore, they are not incentivized to work on projects that are outside the scope of their effort; even if that effort would eventually benefit the overall product development effort. Due to this resistance to work on projects for the "greater good" of the overall system, many companies have found that the only way to instill "modularization" in their business is to drive this from the top of the company. Several companies have developed a position for a Chief Innovation Officer who is chartered to foster "modularization" in their business practices [5].

8. CONCLUSIONS

This assessment of spacecraft bus types and associated acquisition models shows that there is potentially great value in developing a modular, plug-and-play spacecraft bus architecture. However, based on lessons learned from other applications [5], implementation will have to come from outside the "normal" spacecraft acquisition process.

As government organizations are the primary customers today for spacecraft systems, the government space enterprise will have to act in the role of Chief Innovation Officer to bring about this innovation. It is also unclear what will be the ultimate cost of achieving this innovation. However, it is clear that if it is achieved and history is any guide, it will pay tremendous

dividends in reducing costs of spacecraft in the future, and in advancing their capabilities.

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