Modular Platform Architecture for Small Satellites:

Evaluating Applicability and Strategic Issues

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ABSTRACT: The selection of architecture for spacecraft has traditionally been driven by requirements for high performance and very low production rates. With increasing interest in low-cost small satellites and reuse of designs, modular architecture may play an important role in achieving these objectives. This paper reviews the role and strategic implications of architecture selection for small satellites. Product architecture research from the manufacturing industry is summarized and applied to small satellites. The applicability of modular architecture to small satellites is discussed, as are the classes of small satellite missions that are particularly adapted to this architecture, the strategic issues related to architecture selection, and the limitations this architecture places on the system. The roles of standard interfaces, processes, and protocols (including plug-and-play) in modular spacecraft are also investigated.

INTRODUCTION

In the small satellite world, suppliers constantly work to increase profitability and market share while customers continually demand reduced costs and increased performance. The challenge of reconciling these opposing forces, while significant, is not unique. Manufacturers from many industries have approached this problem, and the spacecraft industry may benefit from applying some of the cost-saving methods that have proven successful for auto makers, personal computer manufacturers, and others. This paper explores the application of product architectural selection theory to small satellites, particularly the feasibility of adopting modular platform architecture for spacecraft.

ARCHITECTURE SELECTION THEORY

A summary of the definitions, types, and selection criteria for product architecture are summarized here to enable a discussion of how they apply to small satellites.

Product Architecture

Product architecture describes the way in which product functions are divided into physical components. Ulrich[1] defines product architecture as the arrangement of functional elements, the mapping of those elements to physical components, and the defining of the interfaces between components. *Because architecture defines the way in which a product's functions, interfaces, and components are specified, it is the single largest factor in determining the flexibility of a product and which attributes can be optimized.*

Product architecture is grouped into two principal types: integral and modular. An *integral* architecture has a complex relationship between functions and physical components (see Figure 1), while a *modular* architecture tends toward a simplified one-to-one relationship (see Figure 2).

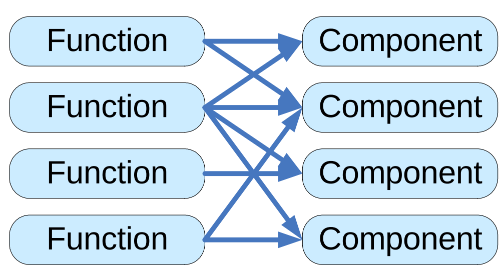

Figure 1. Integral architecture

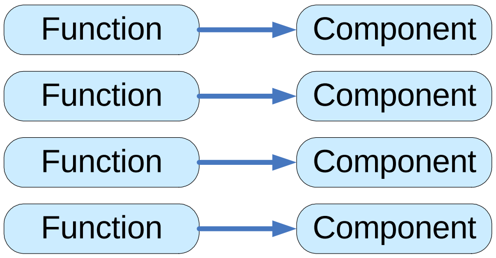

Figure 2. Modular Architecture

Integral architectures allow greater performance optimization or short-term cost optimization, while sacrificing flexibility, standardization, and potential long term cost savings. The complex interfaces and interdependencies within an integral architecture also increase the scope of each product change. For example, replacing a star tracker on a spacecraft may change attitude control algorithms, IMU interfaces, control and data handling software, telemetry packets, and wiring harnesses, each of which could cause additional changes to ripple through the system. In comparison, a modular architecture can be designed to simplify interfaces and interdependencies, reducing the scope of each product change. Modular architecture can be optimized for such areas as flexibility, standardization, and manufacturability. Modular architectures, if well implemented, can also produce significant cost savings over time.

The lowest cost solution for a particular product could be of either architecture type, depending on the characteristics of the product, the market, and the time frame in question. Integral architectures allow mass produced items to be optimized to reduce material or manufacturing costs, as typified by such products as disposable razors or pens. Modular architectures can reduce costs by allowing standardization, reuse of existing designs, de-coupling of manufacturing and assembly processes, or ease of product modification. Many personal computers and automobiles use modular architectures to reduce the number of unique parts while maintaining flexibility to vary a base design to provide some level of product customization.

Modular Platform Architecture

There are various methods for creating modularity, each defined primarily by the way in which the modules are used to create product variety. Modular *platform* architecture uses a set of modules that can be configured to create a number of variant products from a subset of the base modules. Yu et al.[2] note that the application of variation can be either across a product family or across product generations. In other words, multiple variant products can be produced at the same time, or for an individual product, next-generation variations can be produced by introducing upgraded modules.

Platform architecture is particularly well suited for providing variation of the product as a whole while maintaining a large degree of commonality within the product family. Robertson et al. observe that differentiating attributes provide the distinctiveness or customization that end users desire, while commonality provides the cost savings that the supplier desires.[3] While the platform provides the core of basic functions from which variants can be derived, modularity provides the means of variation.

Some of the key characteristics identified by Gershenson et al. that define component modularity from a manufacturing perspective include attribute independence, process independence, and process similarity.[4] Ulrich notes the following characteristics: the extent to which functional elements are separated, the extent of interface coupling, and the type of modularity.[1] These are overlapping descriptions of the independence and interdependence of modules as well as considerations of processes that will affect manufacturing, assembly, and testing.

Modularity at the system level may or may not incorporate modularity at the component level. Integral component architectures with optimized component-level performance can be used at the module level.

Architecture Selection Methods

A number of methods have been developed for evaluating the characteristics of a product and market to determine an appropriate architecture. Researchers have developed various mathematical approaches for selecting and analyzing product architecture.[2, 4-13] Other methods evaluate the system characteristics from a system-level, qualitative perspective. The writings of a few researchers provide insight into the system-level trades, design factors, and market needs that can drive architecture selection.[3-5, 8, 14] For this paper, a system-level, qualitative approach is used to address architecture for small satellites. This approach is discussed in the following section.

SATELLITE ARCHITECTURE SELECTION

The architecture best suited to specific small satellite programs will vary with the objectives, goals, and market forces applicable to each program. This section will discuss selection considerations, the options available for small satellite architectures, and the benefits of platform architecture for this market.

Selection Considerations

The selection of architecture for small satellites must take into consideration the goals, objectives, and characteristics of the industry and market. There are often competing interests that must be balanced, as well as time-varying factors. The unique characteristics of the small satellite market specifically and the aerospace industry generally can create disincentives for certain architectures. A more detailed discussion of these areas follows.

Supplier Goals

System architecture has a direct effect on cost, performance, and flexibility. The architecture, therefore, must take into account the goals of the supplier. Suppliers interested in developing technologically advanced, high performance satellites will have a greater need for the extra performance, simpler development, and short-term advantages of a unique, integral system. Conversely, those interested in developing a family of varying systems that can be configured to meet multiple missions at a lower overall cost are likely to consider the long-term advantages of modular platform architecture.

Architecture should also be compatible with the supplier's investment goals. A supplier focused on developing cutting-edge technology is likely to be more compatible with an integral architecture. This type of firm is more likely to require frequent, broad-scoped changes to a system and to build unique, performance-optimized systems. On the other hand, a supplier focused on lowering cost will be more compatible with modular architecture. Reduction of non-recurring engineering, commonality of processes and procedures, efficient test and integration, and recapture of intellectual and capital investment all require the standardization, reuse, and flexibility of a modular architecture.

The type of architecture recommended for each of these goals is shown in Table 1.

Table 1. Supplier Goals vs. Architecture

Supplier Goal	Recommended Architecture
Push the technological envelope to develop new capabilities	Integral
Develop the lowest cost, highest performance, custom system for a single mission	Integral
Develop the lowest cost, highest performance, configurable system for a group of differing but similar missions	Modular
Increase supplier profitability and market share for a particular market segment while reducing lead time and customer cost	Modular

Mission Objectives

The type of architecture that best fits a particular spacecraft also depends on the mission objectives. Objectives focused primarily on performance characteristics, such as technical capabilities, size, and mass, are best suited to an integral architecture where performance can be optimized. Short term cost objectives for custom missions are also best met with an integral architecture. Long-term costs, however, can be reduced using modular architecture to produce a modular platform that can be adapted, reused, or upgraded. Modular platform architecture, therefore, provides benefits when the primary objective is long-term cost savings across a family of missions. These concepts are summarized in Table 2.

Table 2. Mission Objectives vs. Architecture

Mission Objectives	Recommended Architecture
Maximize performance	Integral
Minimize size	Integral
Minimize cost for unique, custom mission, or for short term	Integral
Minimize long term cost for family of missions	Modular

Market Characteristics

Market characteristics also affect the choice of architecture. Table 3 lists key characteristics of the small satellite market as well as traditional characteristics of the general aerospace market that apply to small satellites.

Table 3. Traditional Market Characteristics

General Aerospace Market
High individual unit costs
High launch costs
Low production numbers
Long lead times
Heavy dependence on federal customers
Severe consequences of product failures
Small Satellite Market
Emerging market
Limited components optimized for market
Focus on research or technology development
Larger proportion of small firms

The most notable characteristics are the low production numbers, very high individual unit costs, and a development process that is heavily dependent on external funding sources (primarily the Federal Government). These characteristics can limit the resources available for private development of platform architecture. The short-term cost savings typical of integral architectures may be easier to justify or fund than the more long-term cost saving potential of platform architecture. In addition, internal development projects are typically protected, which can hinder the standard interface development or adoption processes that are necessary for the full advantage of platform architecture to be realized.

In spite of these obstacles, the proper implementation of modular architecture will enable the realization of significantly lower costs for the segment of the small satellite market in which a large percentage of the missions are experimental in nature and in which the missions often focus on small satellites in order to reach orbit with minimum cost.

Architecture Options for Small Satellites

Three options for small satellite architecture will be discussed in the following sections: traditional bus, common bus, and the modular platform.

Traditional Bus

The traditional architecture of satellites in general, including small satellites, is the integral architecture. A typical satellite bus has complex interfaces and highly integrated components with complex mapping of functions to components. There are a number of factors that lead to this type of architecture, including cost, performance optimization, lot size, and market type. Each satellite contract tends to be focused on a very specific mission. The high performance optimization expected of these missions is often achievable only with highly customized and integrated designs. The small lot size has not created the same standardization incentives that are typical in other industries.

"Common" Bus

The "common" or "standard" bus concepts that have been developed to address the need for greater reuse of satellite investments is a form of "fixed" product portfolio, where variation is minimized across a product line.[2] This bus type is typically an integral architecture with a standardized set of functions and interfaces. It could be viewed as a modular component within a larger system, but it does not include modular concepts within the bus to any great extent.

When variations are minor between products, essentially duplicating the product, or when variations are limited, allowing a few options that are well understood and well defined, this option can be very effective at reducing cost, risk, and development time. However, performance requirements, mission focus, and customer expectations can vary significantly between typical satellite projects, limiting the usefulness of this type of architecture for spacecraft. Large communications satellites that have a high level of similarity across multiple customers may be able to employ this architecture effectively; nevertheless, a well-designed modular system would likely be more effective over time at reducing costs as initial designs begin to vary between customers or across generations of satellites.

Modular Platform

Although not common, varying levels of modularity or platform architecture have been implemented on satellite programs. Even traditional satellites will often divide groups of components into equipment panels or equipment bays. A completely modular platform goes beyond this grouping of components or standardizing of interfaces and incorporates modular concepts from the top level down and across individual programs. The concept of a platform is to create a set of modular building blocks that provide the core, or common, function set and variant modules that are used to differentiate the final product. This provides cost savings, risk reduction, and shortens development cycles by, for example, reuse of the common modules and reuse or standardization of assembly, integration, and test equipment or procedures.

For small satellites, this approach would allow multiple mission types to be supported by the common set of modules, with variation where required to support specific requirements. For example, a bus built with modules that allow various communications equipment or scalable power systems would be adaptable for a number of different missions.

The characteristics of small satellites are well suited to implementing modular platform architecture. The commonality of functions within groups of satellite programs is well suited to take advantage of modular platform architecture, if the loss of performance inherent in this type of system is acceptable. The functional independence of the subsystems, mission similarity, system commonality, process similarity, process independence, and potential for interface standardization are all indicators that small satellite programs would benefit from platform architecture.

Benefits of Modular Architecture for Cost-Driven Small Satellite Missions

The greatest benefit for modular platform architecture, as has been noted, is provided for the group of missions or products that are focused on cost objectives rather than performance objectives – specifically, the reduction in cost for a family of satellites or generations of satellites. Modular platform architecture can help achieve the goals of this subset of the market by:

- Reducing non-recurring engineering (NRE) by reusing both satellite components and ground support equipment (GSE),
- Increasing the level of commonality and simultaneously increasing the potential design variation,
- Easing the incorporation of new technology or new variations by limiting the scope of individual changes on the system, and
- Enabling a trade of performance optimization for cost, flexibility, or standardization optimization.

Each of these benefits eventually results in a reduction of cost. The ability to produce multiple types of satellites from a single core platform while maintaining some level of customization or optimization through module variation (e.g. exchanging battery sizes or reaction wheels to fit most closely with the mission requirements) increases the scope of missions that can be supported from a single set of designs. The standardization of the modular interfaces reduces the effects of changes, either within a module or by exchanging a module. The ease of replacing a module and the standardization of the interface significantly reduce the effort required to introduce new technology within a single module. All of these examples introduce efficiencies in design, assembly, integration, test, or upgrade.

MODULAR PLATFORM IMPLEMENTATION

This section will address how modular platforms can be implemented on cost-driven small satellite programs, the limitations that must be addressed, and the role that standards play in implementation.

Elements of a Modular Satellite Platform

The developer of a modular satellite platform must take into consideration the specific product, supplier, and market goals. While there is much that must be tailored to the specific application, the general principles or elements of modular design will be common to every application. This section discusses these elements of a modular satellite platform.

Commonality and Variation among Satellite Designs

The small satellite market includes a wide range of missions, sizes, performance, and technologies. Within this vast trade space there are common elements that could allow multiple missions to be supported with common hardware or even a common satellite bus. This commonality is one of the key elements for modular architecture. The division of common functions and variations is crucial to a well designed, flexible system.

Areas of functional commonality are easily seen in the subsystems typical of spacecraft. Attitude control, attitude determination, data processing, commanding, telemetry, communications, power generation, and power storage are common functions that all, or nearly all, satellites perform. Modules are created from these areas of commonality by carefully dividing them into distinct, common functional elements. Where functions and performance are similar, the same module may be used. Where different, other modules may be created that scale the performance appropriately, eliminate the function if not required, or replace it with other methods of performing the same function.

In addition to common modules, interfaces to the modules must have a defined level of standardization and commonality. The replacement of one battery with another is greatly simplified if all interfaces (mechanical, electrical, and software) are common. Careful planning can ensure that the number of unique interfaces is minimized.

Variation is typical within some subsystem functions, as well as within specific missions. Lifetime and orbital parameters, such as altitude, inclination and pointing requirements, are a few examples of mission specific variation. Performance requirements, methods of momentum dumping and station keeping, levels of power generation and storage, accuracy of attitude determination and control, and data processing requirements are examples of variables that must be taken into account for each satellite mission.

Although variations can be significant between classes or families of satellites, within a class or family of satellites much of the hardware and components could be designed to be common. The analysis of where variation is required and where the divisions of functions and modules will best serve commonality and variation must be a carefully-planned activity.

Functional Independence

A second key element for architecture selection is the level of functional independence. The traditional separation of satellite functions into subsystems enables a high degree of functional independence. Although there can be a high degree of coupling within a subsystem, traditionally the subsystems have been designed, tested, and integrated with a high level of functional independence. This independence allows for a high degree of modularity.

Interface Standardization

The ability of the design to allow standardization of the interface, in whole or among subgroups, is the next element of modularity. For small satellite components there is not a well-defined standard for mechanical, electrical, or software interfaces. Many components have adopted the Mil-Std-1553 or RS-422 standards for electrical interfaces, but these standards are far from universal. It does appear, however, that standardization could be implemented to a substantial extent. Any architecture chosen for small satellites will most likely need some level of flexibility to handle components that are not easily adapted to a standard interface.

Process Independence and Commonality

Although separate issues, process independence and process commonality are related and overlapping. The degree to which manufacturing, assembly, integration, and testing processes are independent from one another and the degree to which each process is similar is heavily dependant on product architecture. For small satellites there is much that is independent, much that is common, and much that is combined.

The traditional division of subsystems allows many of the assembly and testing processes to run in parallel. The use of simulators further enhances the ability to independently test each subsystem.

Many of the tests required to qualify and accept components are nearly identical. Although the magnitudes vary, each component must have some level of vibration, thermal cycling, and thermal vacuum testing. Electrical components usually require testing of electro-magnetic signature and interference sensitivity.

A number of financial and schedule advantages can be realized by creating commonality of processes. A common qualification process, for example, should create efficiencies both by reducing the number of different processes, the training required for each process, and the non-recurring engineering required to create each process in the first place.

Independence of processes can occur simultaneously with process commonality. A common qualification process that is independent of design processes or assembly processes, except in the order in which they occur, simplifies the creation and flow of each individual process.

Limitations

Platform architecture, like any other, has its own set of limitations. The following two sections describe the most important limitations: the trade-offs (performance and development cost), and the reliance on intelligent development to realize the full benefits of modular architecture.

Cost of Modularity

Obviously, modularity comes at a cost. As has been implied previously, performance optimization is traded for the multiple benefits of modularity. In general a modular system requires more mass, more volume, and often more component capability than would be required with a customized, integral design. Mass and volume are generally greater due to the standardization of the interface, which cannot then be optimized for individual applications. In order to standardize, the greatest capability or minimum performance required for any particular characteristic must be applied uniformly across the interface. For characteristics that vary significantly between applications, a standardized interface can add significant overhead. The interfaces must be carefully designed to minimize this issue.

If modularity is implemented at the module level but not the system level, the trades will be similar to the system level trades. The only design overhead required at the module, or component, level is the standardized interface.

Another cost to consider is the initial investment. A well designed modular architecture is likely to require a higher initial investment to determine how to split out functional units, develop the common core units and variants, and design the standardized interfaces and processes. This additional effort is performed with the expectation of decreased recurring unit costs.

Intelligent Development

As with most development efforts, the full extent of benefits from modular architecture is limited by the implementation. There will be a difference in benefits between poor and intelligent implementation.

A poor implementation with poorly selected interfaces, poorly defined functional modules, and poor reuse of modules for variant designs will result in a cumbersome, inflexible system that loses the advantages of modularity while adding the performance disadvantages inherent in modular designs. The reuse of components, as implemented in the "common" bus architecture, has some cost advantages; "blindly reusing space systems, however, is not the answer,"[15] as Caffrey noted. Forethought into the specific objectives and requirements of each application is required to choose the architecture best suited to the application.

The Role of Standards

The use of standards for processes, interfaces, minimum performance levels, and a myriad of other characteristics is common throughout the aerospace industry. The use of standardized products and standard interfaces is not as common. There is much that could be done within the small satellite industry to improve product and interface standardization. Implementation of such standardization, however, hinges on the benefits standardized products would have to this industry.

Standardization of products is implemented for three principal reasons relative to a spacecraft application: to improve interface compatibility, to increase competition, and/or to reduce support resource requirements. Improving interface compatibility ultimately saves time, and therefore money. Increasing competition by allowing multiple vendors to compete for standard products provides incentives for cost reduction, quality improvement, or performance improvement. Increased competition can also improve product availability. And finally, standard products allow standardization of fabrication, assembly, test, and support, reducing the number of unique resources that are required to support each product.

Standards do not directly affect performance but can lead to performance improvements. Caffrey et al.[15] list a number of benefits specific to interface standards, including broadening implementation, reducing learning curves, modular innovation, reducing risk and uncertainty, economies of scale, and shifting focus from systems to subsystems.

MODULAR ARCHITECTURE EXAMPLES IN THE SATELLITE INDUSTRY

Although the "common bus" architecture is used more often as an alternative to traditional architecture, modular platform architectures have been used in the satellite industry. Three types of modular architecture appear in the literature: modular shelf architecture, thrust tube and equipment bay architecture, and panel and frame architecture.

The shelf architecture is evident in AeroAstro's SCOUT,[16] the Brazilian SACI,[17] and the core electronics sections for many of Surrey Space Technology, Limited (SSTL) satellite designs. This type of architecture is particularly well suited to designs with common form factors. These designs appear to be strongly influenced by electrical engineering concepts and usually have well-defined electrical and mechanical interfaces between shelves. The removal of heat from the assembly and the fixed interface (particularly where the shelf stack can grow only in one dimension) appear to be the greatest drawbacks for this architecture.

The thrust tube and bay architecture is one regularly used for satellites. This architecture has a central cylinder along the thrust axis for the primary structure with equipment bays around the perimeter of the cylinder. Many satellites us the central portion of the cylinder for the propulsion system. The equipment bays can be modular in nature, or the entire assembly can be an integral module to which the payload and other equipment attach. It appears that generally the modular structural frame is the only modular portion of the architecture. The satellite designs for both NASA GSFC's SMEX Lite, shown in Figure 3, and the British MiniSIL[18] use this architecture. The modularity of these types of designs is generally compromised by the level of dependence between each bay. The mechanical aspects of the modularity do not appear to be coupled with electrical and software modularity, and the interfaces between modules are often not clean.

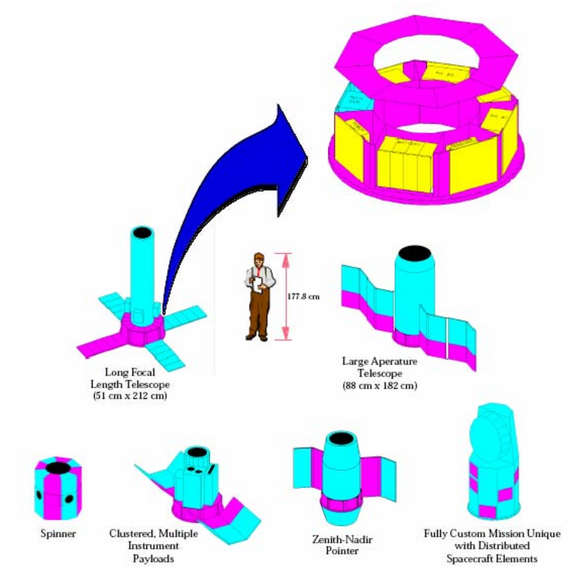

Figure 3. NASA GSFC SMEX-Lite platform as a modular component of satellite observatories[19]

The final architecture type found in the literature is a panel and frame architecture. This architecture is evident in the NASA GFSC Multimission Modular Spacecraft (MMS) design. MMS, shown in Figure 4, was designed specifically to be modular, dividing the power, attitude control, and data handling functions into separate modular panels. These modular panels are attached to a triangular frame that includes the spacecraft and payload interfaces and can include a propulsion module and power generation hardware (solar arrays). MMS was used for the Solar Maximum Mission, Landsat 4 and 5, and the Upper Atmosphere Research Satellite. The modules were designed to be orbital replaceable units for some of these missions, allowing on-orbit servicing or replacement. This implementation is the most modular of the existing architectures studied for this paper.

NASA GSFC has addressed some of the more troublesome issues of modularity that satellites face, particularly the electronics interface and architecture. Their work with the Essential Services Node (ESN) addresses the desire for “plug-and-play” capability. The ability to remove a module and replace it with another module with minimal impact to the remaining modules, and the ability to self identify and automatically reconfigure, are highly desirable attributes that the computer industry has developed for their “plug-and-play” implementation. GSFC uses the ESN to provide these key capabilities, which then enable the implementation of a common electronics bus to which each module can connect. The basic electrical architecture shown in Figure 5 enhances the modularity

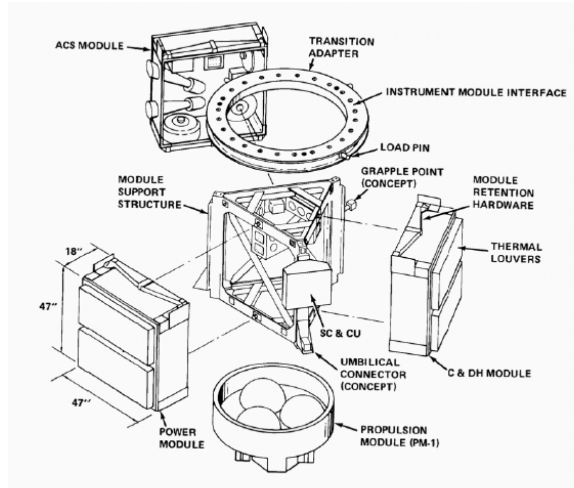

Figure 4. NASA GSFC Multimission Modular Spacecraft[20]

of the design. A modular architecture that incorporates this modular electrical architecture with a corresponding software architecture and modular structural architecture would capture the benefits that modular platform architecture promises.

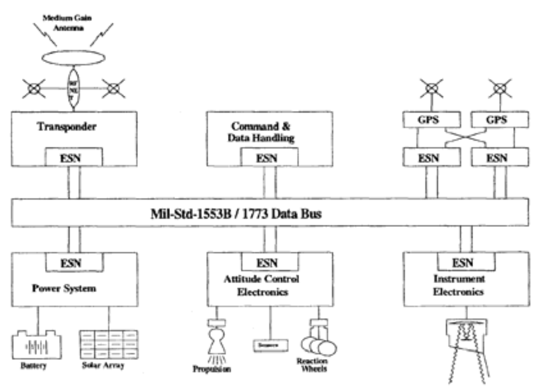

Figure 5. NASA GSFC Modular Essential Services Node (ESN) provides a common interface for the data network.[21]

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