

Modular Architecture and Product Platform Concepts Applied to Multipurpose Small Spacecraft

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ABSTRACT: A product platform may be considered as a set of common parts, processes and interfaces that are shared across a family of related products. The product platform methodology has been successfully employed in a range of design and manufacturing sectors, particularly in the automotive and computer industries, and in consumer electrical goods. The power of the product platform concept is that it allows common elements to be used in the production of a whole family of product variants, giving time and cost improvements whilst still allowing customisation. Variety in the product family is possible from a standard set of modules, while the total parts count in the family is reduced.

This technique may be usefully applied to the design and production of spacecraft, particularly semi-standardised multi-use platforms. This paper examines the relevant literature in product platform and modular design research, with real-world examples from other industries. It then addresses the possible module structure of a spacecraft, via functional decomposition, and proposes a set of variants which could comprise a suitable product family. These variants are selected to satisfy the mission set to which a multi-use small spacecraft design may be applied. A structured approach for enabling modular spacecraft architectures is then suggested.

INTRODUCTION

This paper examines the concept of product platforms and modular architecture applied to commercial, multipurpose small spacecraft.

Missions utilising multi-purpose small spacecraft platforms have a number of significant advantages over those employing bespoke vehicles.

One key element is time-to-flight. Designing a spacecraft from scratch will almost always take more time than designing a mission around an existing platform. In addition, an established commercial program brings with it an existing operational and logistics infrastructure – including supply chains, and established learning curves and knowledge base of the engineering team.

The Swedish Freja minisatellite took 5 years to develop to launch readiness, as it was an entirely new design, and a new type of project for the organisation involved (the Swedish Space Corporation). However, it is estimated by the project team that a similar platform could subsequently be built in 24 to 30 months, due to design heritage and advance knowledge regarding procurement and supply chain issues. An associated labour cost saving of 10-15% would also be expected from such a schedule reduction.⁸

There is also the likelihood of gaining more quality and performance per unit cost, as the supplier, in the course of their own R&D, has already absorbed the bulk of the design phase costs. There is often also

lower technical and programmatic risk, due to demonstrated designs/equipment, and greater knowledge about the systems and processes.

These potential benefits to a customer make a multipurpose platform a marketable commercial item. However, producing a spacecraft platform that is suitable for application to a range of different mission types is a far from trivial task. Employing modular architecture and a common product platform is a key enabler in achieving this.

PRODUCT PLATFORMS – A FRAMEWORK FOR MODULARITY

Many industries, in particular electronics, automobile, and consumer electrical, operate in an environment where multiple, related products are offered. These products may be aimed at different market segments and/or different market niches within the segments.^{11,12} To be competitive, manufacturers have moved from mass production to mass customization, where there is greater product variety coupled with reduced product life cycles. Mass customization has been largely enabled by the development of the concept of product platforms and product families.

The precise definition of a product platform varies quite widely within the literature, but a fairly general and non-industry-specific description may be as follows:

“A product platform is a set of subsystems and interfaces developed to form a common structure

from which a stream of derivative products can be efficiently developed and produced.”¹³

Essentially, the platform is the set from which a family of different, but related, products can be produced. The idea is shown in Figure 1.

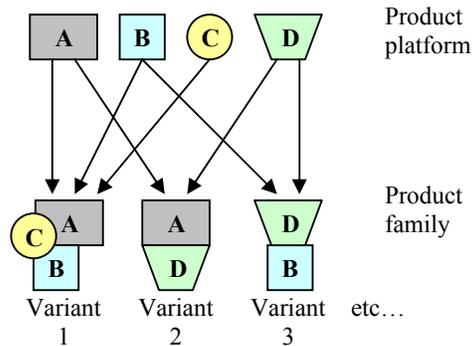


Figure 1. Example of a Product Platform and Product Family

The philosophy may be best illustrated by some brief examples of successful product platform strategies.

Within the automobile industry, the Volkswagen Audi Group offers the brands Audi, VW, Skoda and Seat, each targeted to a different market segment, and each largely perceived by customers as forming an entirely separate set of products. However, each of these brands is based on a common product platform, consisting of numerous parts including front and rear ends, front and rear axles, brake systems, and exhaust systems.^{2,3}

An illustration of the potential economic benefits of a successful product platform strategy is given by the case of Black and Decker power tools.¹¹ In the early 1970s, Black and Decker offered a product line utilizing 30 different motors and 104 different armatures. In 1971, a management decision was taken to adopt a product family approach, using standard components. It was hoped that this would reduce manufacturing costs, improve performance, and allow the products to be more easily upgraded.¹⁴ Implementation of this new program involved a (FY1971)\$17.1M commitment with an anticipated seven-year break-even period. After three years the project was completed, and the new product platform immediately afforded substantial benefits:

- Motor manufacturing savings of \$1.28 million per year
- Motor manufacturing labour reduced from 600 to 171, giving savings of \$4.6 million

- Reduced numbers of components, with lowered storage costs due to smaller stock levels
- Vastly reduced new product development costs, leading to new products on a weekly basis for several years
- Break-even after about half the expected time
- Savings to the end customer of up to 50% on product prices

It may be appreciated from the above that there are key benefits to be gained from a product platform strategy, but the industries so far mentioned are very different to the space industry. How may product platforms be applied to spacecraft?

Modular Architectures for Spacecraft

The mass customization industries where product platform theory has evolved are characterized by high volumes and (generally) relatively low unit costs. Conversely, spacecraft manufacture is characterized by very low volumes and extremely high unit costs. It can, however, be argued that the elements of the product platform strategy that are successful in mass customization are also applicable to the space industry. Indeed, the product platform concept has been applied by JPL to the architecture of interplanetary missions,⁷ and by AeroAstro to spacecraft communications subsystems.⁴ The key to space application is the modular architecture that is the main feature of a product platform family.

Modularity may be viewed as similarity between the physical and the functional architecture, and minimization of incidental interactions between physical components.¹⁵ A modular system may therefore be defined as one that is composed of a number of self-contained units, which are easily removed and replaced without requiring significant architectural changes to the rest of the system. The replacing module may have a different performance, but it will still interface with the existing system.

Building up spacecraft systems out of modular “building blocks” has a number of advantages, many of which are particularly applicable to a multipurpose spacecraft.

System upgrading

If all missions using a commercial, multipurpose spacecraft had the same set of requirements, there would be little benefit to designing a platform to be modifiable or upgradeable; a single design that met the requirement set would suffice. However, requirements vary widely, and what may be a perfect platform for one mission may be entirely inadequate for another. For this reason, an effective multipurpose spacecraft design will have the option to be upgraded to a higher performance level (at

increased cost). The easier the upgrade process can be made, by limiting the impact and redesign incurred on the rest of the system, the smaller the cost increment. A modular spacecraft, at its most idealised, can merely have the under-performing subsystem module unplugged and replaced with a higher-specification one, with the rest of the spacecraft being essentially unaffected.

When producing a multi-purpose spacecraft platform that has different higher-performance options above a standard baseline, there will often be the problem of “wasted performance”. If a mission requires just slightly more capability than a particular option can provide, it must move to the next performance increment. Where the increments are large, there is a lot of capability or performance that is not necessary, but that still must be paid for. This is illustrated in Figure 2. If there is too much wasted performance, it may be cheaper to produce a purpose-built platform that exactly matches the required performance.

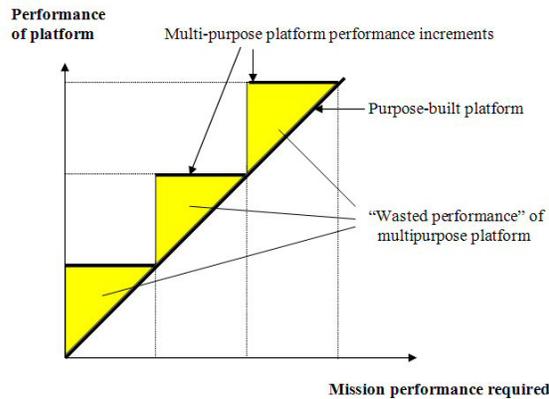


Figure 2. Platform Performance vs Required Performance for Purpose-Built and Multipurpose Spacecraft

A range of modules with different capabilities, which can be easily interchanged, give a greater number of possible performance increments. This can minimise wasted performance. They also enable only the particular under-performing subsystem to be changed, so that unnecessary capability enhancements to other areas are avoided. In the ideal case, the modular multi-purpose spacecraft “performance curve” can become much closer to that of a purpose-built platform.

Integration and testing

A spacecraft that is made up of discrete modules can benefit from a greater concurrency in the integration process. Each module may be assembled, and tested at module level, in parallel. Standard interfaces between modules also afford a less complex final

integration process, with a more efficient learning curve for the AIT team, as the method for integrating each module is similar.

Decoupling of the modules, with respect to data and power, reduces the amount of “de-bugging” required when modules are interfaced together.¹ Standard interfaces also mean that test equipment can be much more standardised, and much GSE can be re-used for later spacecraft even if modules of different “rating” are being used. The flight qualification process can also be streamlined, by enabling much of the structural testing to be performed at module level.

A full engineering model for each spacecraft produced using the modular platform is not necessary; an appropriate model can be assembled out of a “test suite” containing an EM of each module. Test models can be built up of structural and/or electrical models as necessary, and mission-specific flight software and payload test models added. This approach can then enable a protoflight model philosophy, with test levels of the PFM minimised.

The reduced integration and test timescales enabled by subsystem modularity have been demonstrated in the past. NASA’s Goddard Space Flight Centre compared AIT timelines for spacecraft employing the Multimission Modular Spacecraft platform, and comparable spacecraft using non-modular designs, and a marked timeline benefit was shown, as shown in Figure 3.

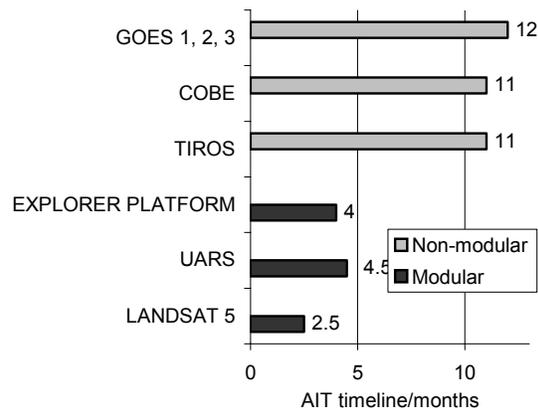


Figure 3. AIT timelines for modular vs non-modular GSFC spacecraft.⁶

Reducing AIT duration offers valuable cost savings, and helps to meet the goal of reducing time-to-flight. It is also to be expected that lessons learned in the test process of the first spacecraft in the series will further reduce the timeline for successive spacecraft.

Configuration design

With standard modules and standard interfaces between them, the design of the spacecraft configuration is made much simpler, and therefore quicker. Compatibility between subsystems is already “designed in”. It is then mainly a case of sizing/selecting the modules according to the requirements of the particular mission.

Simplifying the configuration design process is extremely beneficial from a commercial perspective. When bidding to produce the spacecraft for a particular mission, there may often be very limited time to produce a technical solution proposal. Standard modules, and known configuration options, with clearly understood performance capabilities, can give a competitive edge by ensuring that only missions which are within the scope of the design are bid for, reducing time and effort being wasted on over-optimistic proposals. This strategy also allows more accurate schedule and cost forecasts to be made.

The critical factors that enable modularity are the interfaces between the modules. This includes both the properties of the interfaces, and where the interfaces lie, i.e. how the onboard functions are partitioned into the separate modules.

Properties of the Interfaces

A system is modular if its sub-units can be removed and replaced with other sub-units. It therefore follows that the interfaces between these sub-units must be standardised. For a spacecraft, this would imply that if, for example, an attitude control module was replaced by an upgrade, the new module would “look” the same as the original from the point of view of the rest of the spacecraft. To achieve this, we must define what it is that makes a module look the same, i.e. what are the interfaces that must be standardised?

The different interface types may be defined as follows (these are generally applicable, not specific to space systems):

- Mechanical
- Thermal
- Power
- Data
- Software

Interfaces are generally defined and described by Interface Control Documents (ICDs) and Interface Development Documents (IDDs). These documents should contain sufficient information that no further knowledge of the item described is necessary for the design of a connecting item and the mating interface.

Positioning of the Interfaces

Determination of the positioning and necessary characteristics of the interfaces is achieved by conducting a breakdown of all the functions that are performed onboard a typical spacecraft. This identifies the inputs and outputs required for each function, and their sources and destinations, and shows how the functions performed must interface/interact with the other subsystem functions on the spacecraft.

Another key consideration for enabling a modular system is that elements of the system that may need to be changed independently must be de-coupled from one another. This means that the minimum number of system elements is affected by a performance upgrade or alteration. Such considerations will have to be made once the system requirements specification has been performed, and the performance increments expected of the system have been determined. It should also be noted that in the case of a multipurpose spacecraft, decoupling of the payload from the spacecraft to the greatest extent possible is essential.

Functional partitioning

To be most effective, a modular system should be partitioned such that the sub-units formed are largely single function. This means that individual functions can be upgraded as required, without making any unnecessary changes to subsystems whose performance is already suitable for the mission.

Identification of suitable positions for inter-module interfaces can be achieved by functional breakdown analysis of the spacecraft system. This analysis decomposes all the functions that take place on board into sub-functions, and identifies their inputs and outputs. The process can be continued to deeper and deeper levels, although, once lower levels are reached, the functional analysis becomes much more dependent on the particular hardware being used.

A PRODUCT PLATFORM FOR A MULTIPURPOSE SMALL SPACECRAFT

To determine modules and interfaces for the case of a multipurpose small spacecraft, a functional breakdown analysis was performed for a range of small spacecraft mission types. Applicable mission types were identified as:

- Astronomy
- Space physics
- Interplanetary
- Microgravity
- Earth observation

- LEO communications
- GEO communications

A brief description of these mission types is shown in Table 1.

Mission type	Description	Example missions
Astronomy	Study/image astronomical bodies in various wavelengths, from RF to gamma rays.	Odin, ALEXIS, HETE, CATSAT
Space physics	Plasma physics, study of electromagnetic fields, particles, solar-terrestrial interactions. These missions often study the near-Earth environment.	SAMPEX, SROSS, Equator-S, TRACE, Freja, Orsted, FAST
Interplanetary	Deep space exploration Planetary probes, flybys	Clementine
Microgravity	Study of physical/biological processes in a very low gravity environment.	Biokosmos, Express 1, BREMSAT, EURECA
Earth observation	Remote sensing of the Earth's surface and atmosphere, in various wavelengths. Active (e.g. radar) or passive detection.	Orbview, SeaWIFS, GFO
LEO communications	Store-and-forward messaging and mobile voice communications.	Orbcomm, Iridium, FAIsat
GEO communications	Broadcast services.	

Table 1. Identified mission types applicable to a small spacecraft

Technology demonstration was also found to be applicable as a mission type; however, in the context of characterizing a “typical technology mission”, it was found to be more appropriate to class the mission with that for which the technology is being demonstrated, e.g. Earth observation where a remote sensing technology is being tested.

The key functional requirement areas that characterize each mission type are summarized in Table 2. This allows specific function areas to be related to these mission types. The function areas studied in this way are attitude determination and control, propulsion, power, data handling, communications, and structures and mechanisms. Thermal functions were found to often be more a distributed rather than an identifiable single subsystem or cluster of subsystems.

Each mission type may be thought of as a potential variant in the spacecraft product family. A simplified illustration of the resulting variant-function matrix is shown in Table 3.

This matrix allows the possible positions of interface boundaries to be identified. The interface positions define the points at which the spacecraft would be divided into discrete modules, which would be interchangeable without significant impact on the remaining system. Where there are thick clusters of function utilization across many variants, there is a good case for incorporation of these functions into modules. Such modules are then likely to become part of the product platform.

In a similar way, the generation of this type of matrix may also be performed to examine existing spacecraft product sets. Equipment items can be broken down into their functions – what they *do*, rather than what they *are*. This can then be used to determine applicability of existing items to a move to a platform-based architecture.

The variant-function matrix also allows the identification of sparse clusters, such as the use of radioisotope generators for power raising, the requirement for a re-entry or retrieval function, and the deployment of structural booms (often used for mounting sensitive instruments away from the main spacecraft body in space physics missions).

Where there are extremely sparse clusters, this indicates that such functions are less suitable for incorporation into the product platform. This further suggests that missions where these are defining functions will be unlikely to be accommodated by the product family variants.

Table 2. Key Functional Requirements Identified by Mission Type

Functional area	Astronomy	Space physics	Microgravity	Earth Observation	LEO Communications	GEO Communications	Technology
Physical accommodation of payload	Large payloads Dimensional stability Accurate alignment Unobstructed fields of view, sunshades	Multiple smaller payloads Boom-mounted instruments	Pressurised container Late access to payload	Large payloads Earth pointed Unobstructed fields of view	Large antenna(s) – may require on-orbit deployment Transponders generally large, high mass	As LEO comms	Variable
Communications & data handling	High data rates High data storage	Lower rates but continuous	Real-time operations may be required	High data rates High storage Onboard image processing	Low requirements for spacecraft data	As LEO comms	Variable
Attitude	3-axis inertial Often anti-sun High pointing accuracy High slew rates High stability	Spin stabilisation common Inertial or Earth-referenced Good pointing/position knowledge	Minimal attitude/orbit control manoeuvres to maintain μg	Nadir pointing 3-axis High stability High pointing accuracy & knowledge	Nadir pointing 3-axis Medium accuracy	Nadir pointing 3-axis Higher accuracy	Variable
Orbit	HEO desirable	Polar/near-polar/HEO	May require re-entry or retrieval	Often low altitude, high inclination/sun synchronous Sometimes repeat ground track Orbit maintenance	May be part of a constellation Orbit maintenance	Orbit maintenance Likely to require kick motor	May often take advantage of cheapest piggyback launch opportunities to any orbit
Power	No specific requirements Fixed arrays possible if anti-sun oriented	Medium, but continuous operation Spin may limit deployed arrays	Potentially high, continuous	High, especially for SAR payloads	High	High (higher than LEO comms)	Variable
Environmental	Payload cooling Avoid thermal shock jitter Radiation shielding High cleanliness for optics	Often fly in high radiation environments Require high magnetic cleanliness	Strict control of temperature, pressure, humidity, ambient atmosphere for payload	High cleanliness for optics	No specific requirements	No specific requirements	May choose higher radiation/thermal environment to test equipment

Table 3. Simplified, Top-Level Variant-Function Matrix for Identified Mission Types

Note that the Table shows the functions that are most applicable to a particular spacecraft platform variant. Some may have multiple applicable elements e.g. interplanetary missions may often use RTGs for power, but some missions may use solar cells/batteries.

Variants	Functions																													
	Attitude Determination					Attitude Control					Propulsion				Power			Data Handling			Comms			Structures & Mechanisms						
	Earth sensing	Sun sensing	Inertial referencing	Star sensing	Magnetic field measurement	Reaction control	Momentum bias	Spin stabilisation	Magnetic torque	Gas thrusters	Kick motor(s)	Hydrazine	Electric	Other †	Electrical power storage	Solar energy conversion	Power control	Radioisotope power generation	S/C data processing	P/L data processing	Data storage	S-Band	X-Band	TDRSS	Primary structural support	Solar array drive	Mechanical deployment	Extend boom structures	Re-entry/ retrieval	
Astronomy		X	X	X		X	X		X	X				X	X	X		X	X	X		X	X	X	X		X			
Space physics	X	X			X			X		X				X	X	X		X		X	X				X		X	X		
Interplanetary		X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	
Microgravity	X	X	X			X			X					X	X	X		X		X	X	X	X	X	X	X		X		X
Earth Observation	X	X		X	X	X		X	X		X			X	X	X		X	X	X	X	X	X	X	X	X	X	X		
LEO Comms	X	X			X	X	X		X	X				X	X	X		X		X	X	X			X	X				
GEO Comms	X	X				X	X			X	X	X		X	X	X		X		X	X	X			X	X	X			

†e.g. solar sailing

DEFINING THE PRODUCT FAMILY

In an ideal case, a multipurpose spacecraft might be designed around a product platform such that the product family included sufficient variants to accommodate any mission from the types identified. However, the “sparse functions” seen previously would effectively dilute the product platform with modules that would be seldom used. The product platform is most powerful when it is composed of a core of frequently re-used modules. It is therefore necessary to define a reasonable scope for the product platform, and the product family that arises from it.

It is clear that for products as complex as spacecraft, not all of the final product can be taken from the standardised product platform. Chandrasekaran⁵ classifies modules that are unique to a product, and have a key impact on the form of the final product, as *form defining modules*. On a spacecraft, the payload may be considered to be a form defining module, as may the modules containing the identified sparse functions. These are not considered to be part of the product platform.

In this study, a suitable scope for the product platform is suggested to be such that it can provide product family variants suitable for the following mission types:

- Astronomy
- Space physics
- Earth observation
- LEO communications
- GEO communications

This range of mission types gives a balance between maximising the range of applicable missions for the spacecraft, whilst minimising the occurrence of too many form defining modules that are not part of the product platform.

The modules that showed the highest frequency were selected to form the product platform. The specific requirements for the modules were quantified by allocating “capability increments”, based on examination of the requirements of numerous previous missions. For example, for structural modules, the increments were defined in terms of mass and volume accommodated; for power modules, the increments were defined in terms of power raised or stored.

Modules Comprising the Product Platform

The modules making up the product platform are as follows:

Structural modules – standard modules, in a light or heavy option, depending on the overall equipment

and payload mass of the final spacecraft. The modules are sized such that the full complement of modules for the highest-specification variant in the product family can be accommodated by 4 heavy structural modules, with sufficient mass and volume also provided to support a payload appropriate to that variant. A wide range of mission types can be supported by different configurations of 3 or 4 of the two types of structural module.

Attitude determination module – two different types, basic and high-accuracy. The standard modules may be customised by addition of other equipment, but the missions identified can be based on one or other of these modules.

Attitude control module – again, two standard types, basic and enhanced. Enhanced module has higher performance and is used for larger variants. Note that this module does not include propulsion for attitude control; this is considered as a separate module.

Cold gas propulsion module – used for attitude control, or potentially as low-cost orbit control for short-lifetime, low-mass missions. (Small) range of tank sizes likely to be necessary.

Hydrazine propulsion – for orbital station-keeping. (Small) range of tank sizes likely to be necessary.

Kick motor – for orbit acquisition. Exact motor parameters variable by mission, but interfaces can be standardised, therefore included as part of product platform.

Data handling modules – standard spacecraft data handling module, additional data handling module dedicated to payload where required, for dedicated processing tasks, autonomous functions etc.

Mass memory modules – modular units in increments of 25Gbit, to provide required data storage.

Communications – modules for S-Band, X-Band, and TDRSS-compatible communications. Antenna configurations mission-specific.

Battery module – modular battery packs in increments of 10Ah.

Power control module – power control electronics, regulation, plus range of switching units as interchangeable sub-modules.

Solar array – standard interfaces, and modular construction of deployed arrays to give power-raising increments.

Product Platform Modules ↓	Product Family Variants →				
	Astronomy	Space physics	Earth Observation	LEO Comms	GEO Comms
Structural Modules (number of modules used indicated)	4	3	4	4	4
Basic Attitude Control Module (small wheels, magnetorquers)				X	X
Enhanced Attitude Control Module (large wheels, magnetorquers)	X		X		
Basic Attitude Determination Module (Earth sensor, magnetometer, sun sensors)		X	X	X	X
High accuracy Attitude Determination Module (Star tracker, IRU, sun sensors)	X				
Cold gas Propulsion Module	X	X			
Hydrazine Propulsion Module			X		X
Kick motor		X			X
Data Handling Module	X	X	X	X	X
Payload Data Handling Module			X		
Mass Memory Module	X	X			
S-Band Comms Module	X	X	X	X	X
X-Band Comms Module	X				
TDRSS Comms Module			X		
Battery Module (number of modules used indicated)	2	1	4	4	5
Power Control & Distribution Module	X	X	X	X	X
Body-mounted Solar Array Module		X			
Deployed-fixed Solar Array Module	X				
Deployed-articulated Solar Array Module			X	X	X

Table 4. Variant-Module Matrix

Table 4 shows five example product family variants, selected for an example mission of each type, based on parameters obtained from a representative previous mission. The modules from the product platform family that are used for each indicated.

The following summarises the key parameters of one of these example missions, an astronomy mission.

Example of a Product Family Variant Applied to an Astronomy Mission

The proposed mission for this case study is to perform astronomical observations at X-ray wavelengths. The mission will involve long durations of observation of X-ray sources, with the spacecraft being re-orientated to observe new sites of interest as required. This is based mainly on the HESSI and XTE missions. The mission parameters are shown in Table 5. A very brief summary of the selection of modules from the product platform that make up a suitable variant for this mission are given as follows:

Structural configuration

A configuration based on four of the structural modules allows the payload to be partially accommodated within the centre of the platform structure. This arrangement would permit launch on Taurus, (the smallest launcher that could accommodate the payload instrument dimensions), or

shared launch on larger vehicles. This also allows for inclusion of a propulsion module if required. The general configuration is shown in Figure 4.

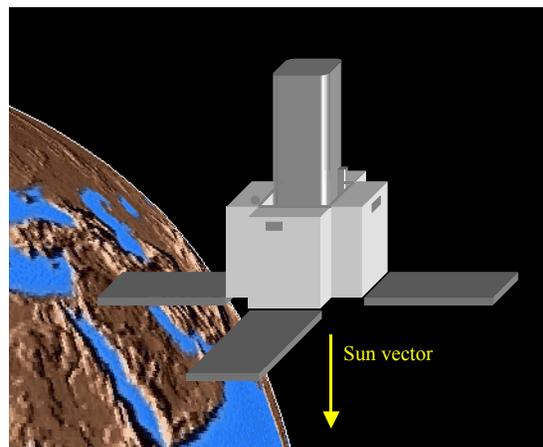


Figure 4. General Configuration of Astronomy Spacecraft Based on Product Platform

Communications and data handling

Due to the large quantities of data produced while the instrument is observing, a high downlink data rate is required. Therefore, the X-band communications module is selected, with the S-band module as an omnidirectional backup and for spacecraft command.

Parameter	Requirement	Remarks
Payload mass	120kg	Instrument based mainly on HESSI X-ray imaging spectrometer ¹⁰
Payload power	110W	
Payload volume	Main instrument 0.45m diameter, 1.4m long Plus electronics boxes	
Manoeuvrability	0.1° per second	To point to new targets of opportunity
Pointing accuracy	Pointing knowledge 5 arcsec Pointing accuracy 25 arcsec	
Data rate	10Gbits over 10-minute observation period	
Data storage	Unspecified	
Processing	Not required	
Attitude	Inertial	
Orbit	450km sunsynchronous	Low orbit avoids radiation Constant sun vector makes anti-sun-pointing easier
Launcher	Unspecified	
Lifetime	2 years	

Table 5. X-ray Astronomy Example Mission Parameters

The data handling subsystem selection is again mainly influenced by the large quantities of data produced by the instrument. As payload processing is not required, the basic data handling option will be used, with additional mass memory modules to store the payload data until it can be down-linked. A baseline level of 100Gbit is used, which will allow data from 10 observation periods to be stored between downloads.

Attitude determination and control/propulsion

The high pointing accuracy and knowledge requirement implies selection of the high-accuracy attitude determination module. However, high manoeuvrability is also required, so the enhanced attitude control module is selected in conjunction with a cold-gas thruster module. Dual paired thrusters will be used in each axis.

Power

The power subsystem requirements are derived from the spacecraft peak power budget shown in Table 6.

As the spacecraft is in a sun-synchronous orbit, and will have a constrained attitude geometry with respect to the sun, the most appropriate choice for the solar arrays is to use a deployed-fixed configuration. Deployed-fixed arrays avoid jitter from drive mechanisms, and the power requirements of the spacecraft are fairly modest so some cosine losses are acceptable. Rigid, rather than flexible, arrays are chosen to avoid any array flexing affecting the pointing accuracy and stability of the spacecraft.

For a 2-year mission, cell performance degradation of (GaAs cells) will be 5.5%. Therefore, a 300W BOL array will give an EOL power of 267W. This meets the peak power requirements plus some margin. Three 100W rigid-panel array modules are used. They will be stowed on the outside of three of the platform modules, and deployed to face the opposite direction to the payload instrument.

System	Peak power requirement /W
Payload	110
Communications	35
Data handling and mass memory	45
Attitude and orbit determination and control	58
Power control	2
Total	250

Table 6. Power budget

Two battery modules supply at least 200W during eclipse. This is sufficient if peak power-draw is not used during eclipse.

A top-level equipment list and mass budget is shown in Table 7. The equipment that is taken from the product platform is shown in bold.

Module	Equipment (bold type indicates taken from product platform)	Mass /kg
Payload	X-ray imaging spectrometer	120
Communications	X-band transponder, amplifier , phased-array antenna S-band transponder, amplifier , omnidirectional antennas	8
Data handling	Data handling module 4x25Gbit mass memory modules	10
Attitude determination & control	4x reaction wheels, magnetorquers Cold gas thruster module Star tracker, IRU, sun sensors	35
Power	3x 100W deployed-fixed array modules 2x 10Ah battery modules	17
Thermal control	Passive	2
Structure	4 light modules	84
Total		276

Table 7. Top-Level Equipment List and Mass Budget for Astronomy Mission Based on Product Platform

Application of the product platform to other example missions generally showed a good product family scope. It appeared that the product platform could be successfully applied to the majority of missions falling within the intended scope of the product family.

The mission requirements specifications used for selecting appropriate variants from the product platform were derived from real missions, and these missions were selected only on the basis of appearing to be a representative example of the mission type. It should be stressed that they were not selected by examining their “closeness of fit” to the capabilities of the product platform and its product family.

However, a general theme noted in all the variants was a higher overall mass than that which would be expected for a purpose built spacecraft, and a corresponding smaller payload fraction. This mass inefficiency is to be expected to some degree, as it is a feature of modular architectures as opposed to unique, structural architectures, but further work is required in optimising the structural modules within the product platform.

GENERAL APPROACH FOR ENABLING MODULAR SPACECRAFT ARCHITECTURES

A general methodology for applying platform concepts and modular architecture in spacecraft design may be summarised as follows:

1. Identify the market for which the product platform is to be used. In this case, small missions utilising a multipurpose platform was selected. This is the target product family.

2. Identify the functions that satisfy the key requirements of all the members of the target product family.

3. Produce a detailed variant-function matrix for all the identified functions and all variants within the product family.

4. Identify the functions that occur repeatedly, and that occur together. This helps to identify suitable module boundaries.

5. Quantify the functional performance required of the modules, with suitable increments.

6. Define the modules that will form the product platform, by selecting only those that contain frequently-occurring functions, and considering interface complexity. Discard form defining modules.

7. Catalogue the platform modules required to form the anticipated variants, and check performance against suitable metrics.

CONCLUSIONS

Benefits from the Product Platform/ Modular Architecture Approach

It is not suggested that the product platform approach will reduce spacecraft costs due to the use of low-cost hardware. Indeed, the actual hardware costs are expected to be similar to, or slightly higher than, those of a comparable “one-off” mission (although some cost reductions may be expected as a result of repeat-manufacture of structural parts, and special agreements for repeat-custom with equipment suppliers). It is largely the reduced life cycle time and reduced parts-count which allows programmatic, and therefore end-to-end, costs to be reduced.

It is expected that, assuming the lowest-cost equipment options are selected for a given performance, the difference in platform hardware cost

between a product platform-based spacecraft and other commercial (or bespoke) spacecraft will be outweighed by the lower programmatic costs.

Importantly for the case discussed in this paper, manpower, overheads, and facilities costs often form a significant proportion of the project costs for small spacecraft (often a greater proportion than equipment procurement, for simple missions). As an example, for the Orsted mission, labour costs accounted for 73% of total mission costs, compared to only 27% for procurement.⁹

The product platform approach also offers manpower savings in the project proposal, and mission design and development phases. The costs of the basic platform design are shared across subsequent projects. Continuous lessons-learned knowledge is also accumulated, as knowledge-retention is a built-in aspect of design based on product platforms. This may also allow later projects to be produced even more quickly and cheaply.

Of course, the shorter schedules also give a direct benefit, in that advantage can be made of “late-availability” launch slots, which other platforms may not be able to meet. If there is no competition for such a launch, the price is likely to be lower. This is of particular relevance to small spacecraft, where launches are often shared or even “piggy-back”.

Drawbacks, and Limitations to Applicability

The key limitation to an organization in adopting a product platform strategy, for any application, is the high initial costs involved in implementation. In the case of a spacecraft, instead of having a single design (which was perhaps designed around a previous mission), that is then re-worked to fit new missions, a range of different configuration possibilities are analysed in advance, and designs modified or even re-worked to enable the product platform-based modular architecture.

This requires considerable up-front investment, which can place limits on which organizations have the resources to adopt such an approach. However, in an ideal situation, much of this is non-recurring, and means that much less time and effort is required to make good responses to ITTs. This strategy obviously only provides a payoff when the program utilizing the product platform continues over the production of many successive spacecraft.

There are certain similarities with a ‘production-line’ approach, in that implementation costs are high, but recurring costs are reduced. However, it is important to note that with this scheme, the spacecraft product family is intended to be differentiated and adapted to

individual missions, rather than being composed of mass-produced, identical products.

SUMMARY

This paper has presented the concept of design based around product platforms and modular architecture, and applied it to design of a product family of small spacecraft. The benefits and requirements of such an architecture have been examined, together with possible limitations to its applicability. The work presented here is part of an on-going study, in which further design and definition of a product platform for a multipurpose small spacecraft is continuing.

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