A FRACTIONATED SPACECRAFT ARCHITECTURE FOR EARTH OBSERVATION MISSIONS

Burak Yaglioglu, M.Sc. [a] and Shinichi Nakasuka, Prof. Dr. [b]

[a] Researcher, Satellite System Design Department,
TUBITAK - UZAY – Space Technologies Research Institute,
TUBITAK - UZAY, ODTÜ Kampüsü, Ankara 06531, Turkey; Tel: +90 535 474 74 75;
E-mail: burak.yaglioglu@uzay.tubitak.gov.tr

[b] Professor, Department of Aeronautics and Astronautics, the University of Tokyo,
Intelligent Space Systems Laboratory, Engineering Building 7,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan;
E-mail: nakasuka@space.t.u-tokyo.ac.jp

KEYWORDS: Earth Observation Platform, Satellite Architecture, Satellite Network, Fractionated Spacecraft

ABSTRACT Removing the physical dependencies between the subsystems, or resources, of a spacecraft, brings several attributes, such as flexibility and robustness, which can be exploited for the benefit of the earth observation payloads. In this manner, an infrastructure network which is composed of resource modules can be put into a sun-synchronous orbit for the benefit of such payloads. However, fractionating a spacecraft and letting the different subsystems fly separately leads to several technological concerns which are related to the shared resources within the fractionated spacecraft network. Regarding these technology implications, realization approaches were discussed via system analysis for shared resources, namely guidance, navigation and control, communications, data handling and power. Notional spacecraft architecture was determined in the light of these discussions and the sizing of the modules within this architecture was performed based on an incremental launch, or one module per launch, approach. By utilizing this infrastructure it is possible to avoid the mission loss due to single point failures and overall capability of the earth observation systems can be enhanced through data processing and routing.

1. INTRODUCTION

A fractionated spacecraft is a satellite architecture for which the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules which interact through wireless communication and power links (Figure 1). The physical independence between the subsystems in this architecture provides the possibility for a plug and play architecture which increases the value of this concept through several attributes such as flexibility and robustness (Brown, 2006a). With these features, it is possible to have scalable, evolvable, adaptive, maintainable and fault tolerant systems.

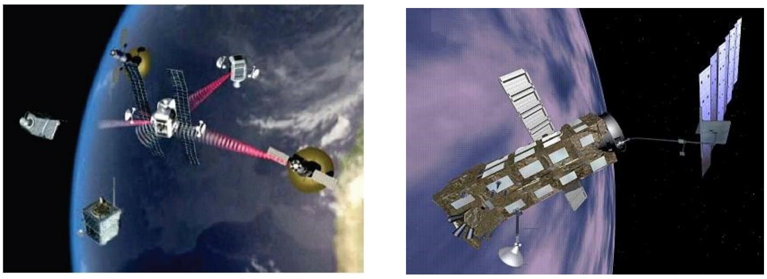


Figure 1: *Fractionated and Monolithic (conventional) Spacecraft (reference: DARPA System F6))*

Since most of the earth observation missions are concerned with sustainability, these attributes could be introduced by an infrastructure network of resource modules which are to serve earth observation payloads. Considering the resources that can be distributed over a network, this infrastructure can provide navigation, data processing and communication capabilities as well as providing external power to such payloads.

Previously this concept was introduced by (Brown, 2006a), (Brown, 2006b), (Brown, 2008) and a few assessment studies were conducted by (O'Neill, 2010), (Mathieu, 2005). Several authors, such as (LoBosco, 2008) and (Guo, 2009), also discussed the realization of fractionated spacecraft and the enabling technologies.

However the technological and feasibility analyses of such a system are still needed. In this manner, a conceptual design study for a network of infrastructure, or resource, and payload modules to support earth observation missions was conducted and the outcomes of this study are presented in this paper.

2 . SYSTEM ANALYSIS, MODELLING AND SIZING

Key to the fractionated spacecraft is the ability to share the resources, which are produced by the subsystems of a satellite, between the physically separated modules. Here, the shared resources can be identified as navigation management, data handling, communications and power management which all together form the infrastructure modules to serve the payload modules within a fractionated spacecraft network. Therefore the system analysis is performed initially in terms of the realization of resource generation and distribution via the infrastructure modules. Then based on this analysis, notional spacecraft architecture is proposed and sizing of this architecture is performed. In this section, system analysis and the sizing method are presented.

2.1 System Analysis

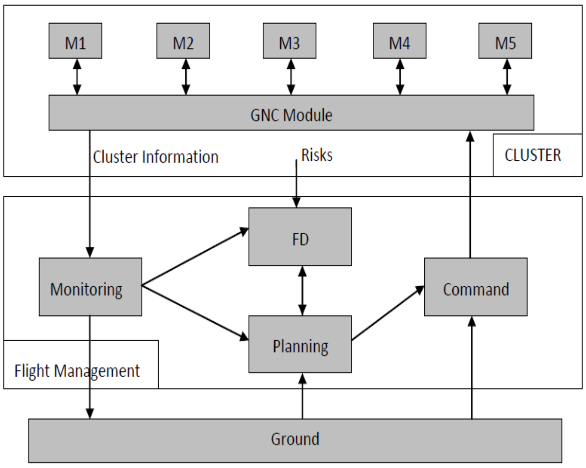
Orbit is one of the most important parts of an earth observation mission. To design the orbit of an earth observation satellite, several trade-off issues are considered in terms of observation frequency, global access, regular ground pattern, regular illumination conditions, aliasing of solar tides and other tides, discontinuities in the orbit and mission lifetime. Based on these, a sun synchronous sub recurrent low earth orbit (LEO) is decided for the earth observation cluster as a first step.

Specifying the orbit of the cluster, technological aspects of resource generation and sharing within the cluster is investigated to define the infrastructure network in detail. In this manner, a guidance, navigation and control (GNC) module is introduced for the flight management of the cluster, a communication and data handling module is also introduced to increase the data processing and communication abilities and, finally, a power module is considered to support power generation, storage and distribution within the network.

Guidance Navigation and Control (GNC)

GNC function basically deals with the determination and control of the orbit and the orientation of a spacecraft. Although the relative positions of the modules within the cluster do not have to be controlled precisely, there is still a need for orbit control to account for the orbit maintenance and also for the collision avoidance. Due to the individual orientation requirements of infrastructure and payload modules, attitude control is another requirement for the modules.

To perform a collision free cluster flying, there are several functionalities to be performed by a dedicated GNC module such as monitoring, commanding, planning and fault detection (FD). Since the frequency of attitude control is much higher than the orbit control, only orbit control is centralized through a dedicated GNC module. In this manner, the architecture of the flight management can be seen in below figure:



Monitoring Function: provides past, present and future absolute and relative navigation information.

Planning Function: responsible for the generation, evaluation and assignment of the trajectories to be followed by the modules in case of the orbit maintenance, ground assignment and contingency operations such as collision or evaporation (loss of inter-satellite links) avoidance.

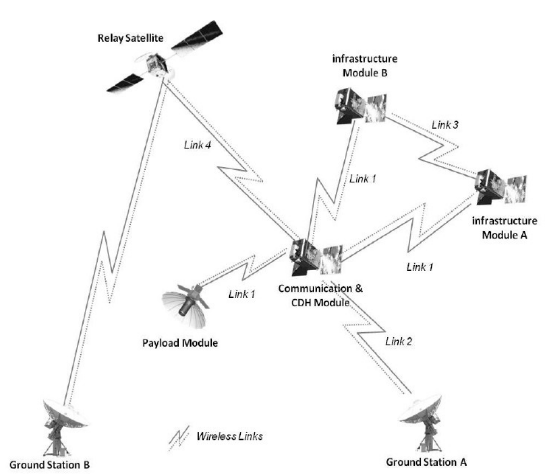
Fault Detection Function: propagates the relative motion to detect the risks of collision or evaporation as well as inspecting the health of orbit control hardware.

Command Function: generates the fuel or time optimal maneuvers and the specific timelines required by the given trajectories from planning function and it distributes these to corresponding modules.

Figure 2: *Functional Block Diagram of the Centralized Flight Management*

Communications and Data Handling (CDH)

Communications and data handling module is responsible for collecting, processing and routing of the payload and housekeeping (HK) data for the earth observation module network. Due to the distributed architecture, there is a need for inter-module, or inter-satellite, links apart from a dedicated space to ground link. In this manner, there are four types of link to be defined within this module network. First is the link between a module and the CDH module, second is the space to ground link and third is the link between any two modules excluding the CDH module. If there is also a need for a link between the CDH module and a relay satellite located in a geostationary earth orbit (GEO) then this becomes the fourth link. Resulting communications architecture is shown in Figure 3.



CDH Component	Specification	
X-Band downlink	500 Mbps	Link 2
S-Band inter-module link (omni-directional)	~10 kbps	Link 1 & 3
Optical inter-module links (1 km range)	~1Gbps	Link 1
Optical inter-satellite link (LEO-GEO)	2.5 Gbps	Link 4
Solid State Data Recorder	4 Tbit / 1.6 Gbps	Data Storage

Figure 3: *Overview of the communications architecture (gif source: DARPA System F6)*

Since the CDH module is desired to support payloads with a high data rate space to ground transmission, corresponding data rate requirements for the payload modules can be reduced. In this manner, a high speed inter-satellite optical link is introduced between a payload and the CDH module to transfer the mission specific valuable data to be processed, stored and transmitted to the ground. Low cost, low mass, low power and compact optical links for this purpose can be designed and implemented for a high data rate link (Leeb). On the other hand routing the commands and HK data can be handled with omni-directional antennas and/or optical terminals. Finally, the high data rate space to ground link, i.e. link 2, can be realized by an X-Band RF link (Hespeler, 2005).

The links between the modules excluding the CDH module, i.e. link 3, would likely include HK and navigation data to be used by GNC module and/or used for power transfer link establishment. For this link, wide beam or omni-directional antennas can be accommodated within the modules. Finally, the link between a GEO relay satellite and the CDH module, i.e. link 4, can be realized by utilizing a high data rate optical link (DeCarlo).

The data storage and processing required within the cluster can be performed by the CDH module which would have a higher storage capability through solid state recorders and a high performance computer. Therefore the storage and processor requirements for other modules can be reduced significantly.

Power Generation and Distribution

A dedicated power module is introduced to support payload modules by generating more power than its need. While power generation is performed by solar cells, power distribution has to be performed by a wireless link since it is desired to have physical independence between the modules.

Previously, the wireless power transmission was studied via radio and microwave transmission (Wikipedia). Currently the focus of the studies is on the laser transmission and electromagnetic induction (Nugent, 2008), (Nugent, 2010), (Simon, 2009). Since the electromagnetic induction is viable over short ranges, laser power beaming deserves more attention with its ability of long range power transmission. Here long range power transmission is also possible via microwave/radio beaming. Although the efficiencies would be higher for the microwave transmission, it is discussed by (Steinsiek, 2004) that the laser power beaming is favored in order to avoid the drawbacks of microwave transmission such as side lobes & spikes, more integration complexity, higher cost, higher mass and sizing requirements of transmitting elements (up to a factor of 50) compared to laser system. As the hardware constraints also favor the laser power beaming, and there would be already solar arrays on board the modules, the power transfer should be performed via lasers.

The overview of the power transmission link using lasers can be depicted in below figure:

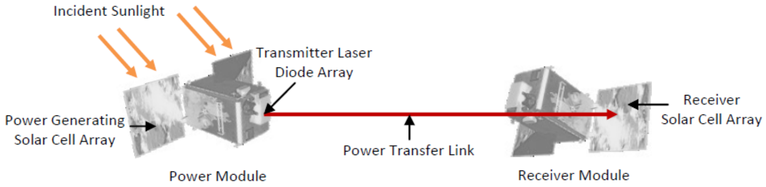


Fig. 4: *Illustration of the wireless power transfer via lasers*

Based on commercially available laser power beaming systems (Nugent, 2008), (Nugent, 2010), power transfer of several hundred watts over a range of 1 km is possible with an overall efficiency around 26%. For short ranges, it is possible to deliver around 1 kW levels continuously with a system having a power density of 1 kW/kg. With respect to its low efficiency, the power module can be used for providing extra power in addition to a baseline power generation by the payload modules instead of providing all the power needed by each module.

Based on above discussions for the system analysis, it can be deduced that a module which provides navigation management becomes the GNC module, a module which can provide higher capability communication and data handling becomes the CDH module and finally a module producing more power than its need becomes the power module.

2.2 Modelling and Sizing

To accommodate the previously discussed capabilities of resource generation and distribution, we can assume a standard satellite bus which has the capability of surviving in the orbit without any assistance. Therefore each spacecraft must have the minimum capabilities of attitude and orbit control, communications and data handling, power management and thermal control. Since fractionating these subsystems would require significant technological breakthrough, it is more viable to fractionate the resources (LoBosco, 2008). In this manner, any increased capability of resource sharing for a baseline satellite bus results in an infrastructure module. If a payload is put to this baseline bus then it becomes the payload module.

For sizing the above mentioned modules, a modular and parametric bus sizing code was developed with respect to increasing capabilities in a baseline bus or accommodating a payload. The basic elements, or the functions, of the bus sizing code are orbit, guidance, navigation and control (GNC), command and data handling (CDH), communication, power, structure and thermal. The inputs (on the left), models of the subsystems and their interactions (on the right) are summarized in Figure 5. The points on upper triangle indicate the feed-forward information from the related subsystems and the ones on lower triangle indicate the feedback information. The information flow is from left to right.

Mission	Mission Life, Launch Altitude
Orbit	Cluster position
GNC	Pointing, slew and rate requirements
CDH	Data rate, subsystem complexity factors
TT&C	Link type, data rate, antenna diameter
Power	Payload and bus power requirements
Structure	Payload mass, spacecraft density and dry mass

Model	*Payload*	*Orbit*	*GNC*	*CDH*	*Comm*	*Power*	*Structure*	*Thermal*
Payload	■	*	*	*	*	*	*	
Orbit		■	*		*	*		*
GNC			■			*	*	
CDH				■	*	*	*	
Communication					■	*	*	
Power						■	*	*
Structure		*	*				■	*
Thermal						*	*	■

Figure 5: *Spacecraft Bus Sizing Code Overview*

The inputs are either payload requirements or initial guesses and are fed forwarded to the related subsystem sizing functions in the order presented above. Here payload requirements can either be the additional resource generation capability for infrastructure modules or the specific requirements for a mission payload. Then the overall code is iterated for more than five times to have the optimized solution of the overall mass, power and size of a specific module. Here the constraints for mass and size are specified with respect to the capabilities of an example launch vehicle (SpaceX, 2010). In this manner the limiting mass and volume were selected as 550 kg and 5.5 m^3 for a LEO orbit of 800 km. altitude and 98.6° inclination. Also it was assumed that only one module is placed in the launch vehicle when a new module is launched. Therefore these constraints directly apply to the sizing of a module. In this way, the launch failure risk would be distributed across multiple launches while the cluster is formed gradually.

3. NOTIONAL SPACECRAFT ARCHITECTURE AND SIZING RESULTS

A bus system which can be considered as an example baseline to introduce either additional resource or a payload is provided by (NEC, 2010) and the specifications are provided below:

Table 1: *An Example Bus System Specifications (NEC, 2010)*

Bus Dry Mass	200 [kg]	***Attitude Control***	3 Axis, ±6.6x10^{-2} [deg]
Bus Power	300 [W]	***Battery, Solar Array***	Li-Ion, TJ – GaAs cells
Bus Dimensions	1x1x0.8 [m]	***Communication***	S-Band, 200 Mbps
Payload Mass	max. 200 [kg]	***Data Bus, Storage***	SpaceWire, 4 GB
Payload Power	max. 600 [W]	***Lifetime***	3 to 5 years

As it was also mentioned in section 2, the increased capabilities in terms of the resource generation or addition of a payload to a baseline satellite bus define the module either as an infrastructure or a payload module. Then the summary of functionality distribution and resource generation within the fractionated spacecraft network is provided in below table:

Table 2: *Functionalities and resources of modules within spacecraft network*

GNC	***CDH***	***Power***	***Payload***
Responsible for navigation management of the cluster	Collects, processes and routes the commands, housekeeping and payload data	Generates and distributes power	Accommodates the mission specfic instrument
Resource:	*Resource:*	*Resource:*	*Resource:*
Absolute and relative navigation processing	Data processing, storage and communication	Power	Mission specific valuable data

In order to increase the robustness of the infrastructure cluster, we can add more communication and data handling capabilities to GNC and Power modules. For example, we can introduce an additional advanced processor, solid state recorders and an X-band communication system to GNC module. On the other hand, an additional relay satellite communication system can be introduced to the power module. Then the final capabilities of the modules would become as represented in below table:

Table 3: *Notional Infrastructure Cluster Resource Matrix*

	Navigation Computer	***Advanced Processor***	***Solid State Recorder***	***X-Band Comm.***	***Relay Satellite Optical Comm.***	***Wireless Power Transfer (WPT)***
GNC	*	*	*	*		
CDH	*	*	*	*	*	
Power					*	*

Using above tables as reference, four types of modules are considered for sizing and evaluation. These are three infrastructure modules, i.e. GNC, CDH and Power, and the payload modules. For each type of module a set of individual requirements, or inputs were given to the sizing code and associated masses, volumes and power consumptions were obtained.

The modules are sized such that there are three infrastructure and five payload modules in the network. For GNC module the navigation sensor and data handling capabilities were increased while for the CDH module the handled data rate was increased gradually. The same was performed for the power module by increasing the amount of transferred power. Finally two cases of payload module were considered as one with power transfer and the other without the power transfer. The summary of the resulting module specifications are provided in Table 4.

Table 4: *The specifications of the infrastructure and payload modules after the sizing*

Module	*Resource Generation*	*Total Mass [kg]*	*Payload Mass [kg]*	*Power [W]*	*Volume [m^3]*	*Lifetime [years]*
GNC	*Flight Man.+ 5.5 Gbps data handling*	*341.3*	-	*391.2*	*1.7*	*10*
CDH	*X-Band downlink + 5.5Gbps data handling*	*382.6*	-	*431.4*	*1.91*	*10*
Power	*WPT of 1300 W + GEO optical link*	*546.6*	-	*137.3*	*3.47*	*10*
Payload[1]	*Mission specific valuable data*	*551*	*196*	*629.6*	*2.75*	*5*
Payload[2]	*Mission specific valuable data*	*548.6*	*220*	*701.5*	*2.74*	*5*

[1] *Without wireless power transfer,* [2] *With wireless power transfer*

4. EVALUATION AND CONCLUSIONS

The presented fractionated infrastructure system results in a cluster of mini satellites where the mass of a module ranges from 300 to 550 kg. Here one module per launch approach was favored for sizing since the launch risk would be distributed across many launches.

Regarding the results presented in previous tables and figures, it can be seen that the capability increase in terms of data handling is achieved with a less mass penalty. Increasing power distribution capabilities within the size limits of micro satellite scale, i.e. less than 100 kg, is very difficult since a power module of 300kg can distribute around 500 W in total. On the other hand, the capability of accommodating a payload mass of 222 kg is possible when power transfer is available. Otherwise, the available payload mass reduces to a value below 200 kg in addition to a significant reduction in available power.

In summary, with an infrastructure of approximately 1270 kg it is possible to provide 1300 W of power, a downlink data rate of 2 x 500 Mbps and 2 x 5.5 Gbps of data handling capability for the benefit of earth observation payload modules. In addition, although the payload modules were sized with respect to the given launch vehicle, they can be also launched together as bundles with another launch vehicle with more mass allowance.

With this study, an insight to technological and realization aspects of fractionated spacecraft was provided. Referring to the system and technology analysis, a notional fractionated spacecraft infrastructure was proposed and sized for the benefit of earth observation payloads. By introducing this infrastructure it is possible to avoid the losses due to single point failures and it is possible to enhance performance of the overall earth observation system through data processing and routing.

When compared to monolithic spacecraft, fractionated spacecraft may have additional costs due to its natural redundancy. However this architecture offers many advantages in terms of flexibility and robustness. In this manner, to be able to assess the feasibility of such an infrastructure concept precisely, the economical cost – benefit analysis, or value centric design, should be performed via the evaluation over these attributes. Then the design outcome shall be the one with the lowest risk and maximum value. This would be the complementing part of this study reserved as a future work.

References

Brown, O., Eremenko, P., 2006a , The Value Proposition for Fractionated Space Architectures, AIAA-2006-7506, American Institute of Aeronautics and Astronautics: Space 2006, San Jose, CA, USA.
Brown, O., Eremenko, P., 2006b, Fractionated Space Architectures: A Vision for Responsive Space, 4th Responsive Space Conference, Los Angeles, CA, USA.
Brown, O., Eremenko, P., 2008, Application of Value Centric Design to Space Architectures: The Case of Fractionated Spacecraft, AIAA-2008-7869, American Institute of Aeronautics and Astronautics: Space 2008 Conference and Exposition, San Diego, California, USA.
De Carlo, P. M., et. al., Intersatellite link for Earth Observation Satellites constellation, Italian Space Agency (ASI).
Guo, J., et.al., 2009, “Fractionated Spacecraft: The New Sprout in Distributed Space Systems“, IAC-09-D1.1.4, 60th International Astronautical Congress, Daejeon, Republic of Korea.
Hespeler, B., 2005, High Data rate Downlink Transmitters for Earth Observation Missions, Tesat-Spacecom GmbH & Co.KG.
Leeb, W., Kalmar, A., Kudielka, K., Winzer, P. J., “Optical Terminals for Microsatellite Swarms”, Instituet für Nachrichtentechnik und Hochfrequenz-technik, Technische Universitaet Wien, Austria.
LoBosco, D.M., et al., 2008, The Pleiades Fractionated Space System Architecture and the Future of National Security Space, Proc. of AIAA SPACE 2008 Conference & Exposition, AIAA-2008-7687, San Diego, CA, USA.
Mathieu, C., Weigel, A., 2005, Assessing the Flexibility Provided by Fractionated Spacecraft, Space 2005 Conference and Exposition, American Institute of Aeronautics and Astronautics, Long Beach, California, USA.
Nugent, T. J., Kare, J. T., 2008, Laser Power Beaming on a Shoestring, Fifth International Symposium on Beamed Energy Propulsion. AIP Conference Proceedings, Volume 997, pp. 97-108.
Nugent, T. J., Kare, J. T., 2010, Laser Power for UAVs, LaserMotive LLC White Paper, Kent WA 98032, USA
O'Neill, M., G., 2010, Assessing the Impacts of Fractionation on Pointing Intensive Spacecraft, Master Thesis, Massachusetts Institute of Technology, USA.
Simon, M.J., Langer, C., Rubin, S., Komush, D., Maciuca, D., 2009, Wireless Power Transfer for Responsive Space Applications, AIAA 2009-6774.
Steinsiek, F., Weber, K. H., Foth, W. P., Foth, H. J., Shaefer, C., 2004, Wireless Power Transmission Technology Development and Demonstrations, 5th International Conference on Wireless Power Transfer.

Web References

NEC Satellite Systems, 2010, NEXTAR, Japan
http://www.nec.com/global/solutions/space/satellite_systems/nextar.html
Open Web Source, 2011, http://en.wikipedia.org/wiki/Wireless_energy_transfer
SpaceX, 2010, Falcon 1 Users Guide, Rev. 7, www.spacex.com/falcon1.php