

FRACTIONATED SPACECRAFT: THE NEW SPROUT IN DISTRIBUTED SPACE SYSTEMS

J. Guo^{*}, D.C. Maessen[†], E. Gill[‡]

^{*}Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, J.Guo@tudelft.nl

[†]Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, D.C.Maessen@tudelft.nl

[‡]Chair of Space Systems Engineering, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands, E.K.A.Gill@tudelft.nl

ABSTRACT

This paper provides a survey of current state-of-the-art technologies of fractionated spacecraft, a new architecture for distributed space systems. The survey covers six aspects: architecture, networking, wireless communication, wireless power transfer, distributed computing, and planned missions implementing this architecture. As a result of this survey, the technology readiness level of each of these technology areas is assessed. Finally, research and development activities at the Delft University of Technology in the field of spacecraft formation flying are introduced. Focus is given to areas where fractionated spacecraft share technologies with formation flying spacecraft.

INTRODUCTION

Fractionated spacecraft represent a novel architecture for distributed space systems. Unlike constellations or formations, where similar spacecraft are spatially distributed, a fractionated spacecraft distributes the functional capabilities of a conventional monolithic spacecraft amongst multiple heterogeneous modules which perform distinct functions and interact through wireless communication links. Although doubts on its economics exist, the fractionated spacecraft is attracting more and more attention from academia, industry and governments due to its advantages of rapid response, enhanced mission and in-orbit robustness, potential for mass production, flexibility with later added features and lowered mission recovery costs [1]. In some sense the fractionated spacecraft may be regarded as a game-changing event in the history of space systems, just like the internet revolutionized data communications.

The term "fractionated spacecraft" is relatively new and has been coined in 2006 by Owen Brown and Paul Eremenko in a series of papers [1, 2, 3]. In August 2006, a workshop dedicated to fractionated spacecraft was held by Defense Advanced Research Projects Agency (DARPA) at Colorado Springs [4]. In 2007, DARPA announced soliciting proposals for a program entitled System F6 (Future Fast, Flexible, Free-Flying, Fractionated Spacecraft united by Information

eXchange) [5]. Eventually in 2008, the DARPA System F6 contracts were issued to teams headed by The Boeing, Lockheed Martin, Northrop Grumman and Orbital Sciences, for the preliminary development [6].

This paper attempts to provide a comprehensive overview on current state-of-the-art technologies related to fractionated spacecraft, including the work being performed at the Delft University of Technology (TU Delft), The Netherlands. The paper consists of two main parts. The first part is a survey of up-to-date research on fractionated spacecraft. As a truly networked system of systems in space, the fractionated spacecraft faces a lot of challenges, such as wireless power transfer, autonomous self-forming networks, and so on. Recent advances in these technologies are reviewed, with the focus on their availability for fractionated spacecraft. Special focus is put on ongoing space missions related to fractionated spacecraft. The second part of this paper briefly introduces research and development activities at TU Delft with a focus on distributed space systems. As an emerging branch of distributed space systems, fractionated spacecraft can be regarded as sharing some technologies with formation flying, such as wireless communication, networking and distributed computing. Potential synergies for technology and programmatic extensions of TU Delft's work in these areas are given.

SURVEY ON FRACTIONATED SPACECRAFT

The generalized concept of a fractionated spacecraft is to break a large monolithic spacecraft into smaller homogeneous or heterogeneous modules [7]. For homogeneous fractionation, the large spacecraft will be replaced with a cluster of identical small spacecraft which can function independently from each other (e.g. formation flying satellites). For heterogeneous fractionation, the large spacecraft will be re-constituted by a cluster of wirelessly interconnected spacecraft modules that each has a unique function such as Guidance, Navigation and Control (GNC), and command and data handling. These heterogeneous modules fly freely in approximately the same orbit. In most references, including this paper, "fractionated spacecraft" only refers to the latter definition.

Although the fractionated spacecraft itself is a revolutionary concept, it is still built on past achievements. From the other side, the fractionated spacecraft also urged the emerging of new technologies. Owen identified four key technologies for fractionated spacecraft: networking, wireless communication, cluster flight, and distributed computing [8]. In this section, a review of up-to-date work on fractionated spacecraft is conducted from six aspects: architecture, networking, wireless communication, wireless power transfer, distributed computing, and planned missions.

Architecture

Research on the architecture of fractionated spacecraft so far focused on the assessments of the architecture. The first article about this can be dated back to 1984 by Molette et al. [9]. In that paper, two main space segment concepts were assessed: the cluster of cooperative satellites and a large platform assembled in orbit. The first one is similar with the concept of fractionated spacecraft. Different concepts are characterized by the required number of modules to be launched, the type of launcher, and the new subsystem to be developed. The main conclusion of this research is that the cluster of satellites is much less cost effective than the assembled platform. However, this conclusion is not convincing because the attributes such as adaptability, flexibility and growth potential are not counted in a quantitative way in their cost-based econometric framework.

Rooney performed a quantitative assessment of spacecraft fractionation using Design Rules [10]. In his work, a known-state spacecraft, i.e. a Boeing 601HP geostationary communication satellite, is used as the example to evaluate

fractionation, which allows reality-based focus on specific engineering. Mission-specific functional elements are divided into appropriately sized fractionated blocks, mission-support common-function elements are distributed across multiple nodes, and the detailed mass properties of each element within the nodes are compared with the known Boeing 601HP mass budget. Rooney concluded that the efficiency of fractionation is very dependent on the type of the mission and, therefore, geostationary communication missions are not appropriate for fractionation from the cost standpoint.

In a series of papers presented by Mathieu and Weigel [7, 11, 12], another quantitative way for the assessment of fractionated space architectures is provided, using Multi-attribute Trade-space Exploration. This method is a customer-centric approach because it assesses fractionated architectures in terms of the attributes. For the purpose of valuing the attributes, a set of possible customers are interviewed for an imaging, a communication and a navigation mission, followed by a multi-attribute utility analysis. Non-traditional attributes, including maintainability, scalability, flexibility and responsiveness are incorporated. The architectures are described by a set of design parameters at both spacecraft and fractionation levels, which forms the design vector. Through varying the values of the design parameters, e.g. numbers of infrastructure modules, or type of power fractionation, the trade spaces of the architectures are explored. An important conclusion of this research is that customers would choose fractionated spacecraft if non-traditional attributes are valued enough, which corroborates the development of fractionated spacecraft.

Brown and his collaborators investigated the architecture of fractionated spacecraft both in qualitative and quantitative ways. In [1, 3], he provided a detailed qualitative discussion about the advantages and disadvantages of fractionated spacecraft, and claimed that the flexibility and the responsiveness of a fractionated system will exceed any penalties. In [2], Brown et al. introduced the value model, which associates the benefit (value) delivered to the user with a given fractionated system architecture. In [13], a methodology to calculate the total system lifecycle cost under uncertainty was presented. The philosophy of this method is: the system lifecycle cost is a random variable with a probability distribution caused by uncertainties throughout the lifetime, and this random variable is the basis for comparison between different architectures. According to this methodology, the lifecycle costs of alternative

fractionated architectures were derived using Monte Carlo simulation incorporating launch and component failure uncertainties. It was found that the total lifecycle costs of fractionated spacecraft are comparable to monolithic spacecraft if the individual modules' design lifetimes are longer. Based on the work in the value-based technology, Brown et al. introduced the value-centric design into fractionated spacecraft [14, 15]. The basic idea of the value-centric design is to formulate the design of fractionated spacecraft as an optimization problem. The fractionated architecture can be defined by a relatively small set of tradable architectural design parameters such as "degree of fractionation" and "distribution of nodes across modules", and a set of attributes, consisting of cost, flexibility and robustness, is folded into the objective function. Then by given different sets of design parameters, the objective function can be evaluated either using the system lifecycle costs method in [13], or using the direct valuation of flexibility and robustness.

Networking

Like connected computers on the ground, each module of a fractionated spacecraft can be regarded as a node, and the whole fractionated spacecraft forms a network connected by Radio Frequency (RF) or laser links. If needed, the elements of the ground segment can also be treated as network nodes.

Brown pointed out that the fractionated spacecraft should be an autonomous, self-forming network of nodes [1], which means that if new modules or new spacecraft join the network, they can be integrated in a "plug-and-play"-like fashion just as for a ground based wireless network. Some existing technologies, such as Internet Protocols (IP), could possibly realize this in space. However, so far the work primarily focuses on formation flying or satellite-ground networking rather than fractionated spacecraft.

Kusza and Paluszek [16] compared lower layer protocols for Inter-Satellite Links (ISLs) in an attempt to identify a protocol for widespread ISL use such that:

- Interaction among different constellations is possible and;
- The addition of new satellites to existing constellations is simpler.

The protocols considered are X.25/LAP-B, TCP/IP, ATM, IEEE 802.11, and CCSDS Proximity-1, SCPS, and AOS. The criteria are comprehensive, including:

- Networking and multiple access capability;
- Reliability;
- Cost effective;
- Unsymmetrical forward and return links (different data rates);
- Limited bandwidth;
- Variable return trip times (RTTs) due to changing inter-satellite distances;
- Single event upsets;
- Antenna obscuration and;
- Limited (processing) power, program memory, and data buffering.

According to these criteria, some interesting conclusions are drawn: ATM does not adequately support multiple access, TCP/IP and CCSDS SCPS are too high up the protocol stack to be considered as a lower layer protocol, CCSDS AOS is not intended for space-space links, and the IEEE 802.11 physical layer would need to be entirely revamped to meet physical layer requirements. The remaining options are the HDLC-based X.25/LAP-B and CCSDS Proximity-1. CCSDS Proximity-1 has many advantages over X.25/LAP-B since it was specifically designed for space-space links. However, when Kusza and Paluszek published their paper, CCSDS was still in Red Book stage (currently it is Blue Book!!) and HDLC had decades of commercial production and existing engineering expertise, even though it was not intended for ISLs. An experimental comparison of two similar implemented systems including a cost estimate was needed to determine whether the benefits built into CCSDS Proximity-1 will outweigh the availability of existing standards such as HDLC or IEEE 802.11. A Spread Spectrum (SS) link (e.g., Direct Sequence, Frequency Hopping) is desired for multiple access, security (jamming, eavesdropping), resistance to degrading and multipath effects, and to allow inter-satellite ranging. If a widely supported protocol is used (e.g. CCSDS Prox-1), communication with different spacecraft close to the 'own' formation becomes an option.

Another interesting and also very exciting work has been reported by Hogue et al. [17]. In that paper, issues related to the use of standard IP for satellite communication are discussed, including:

- Lower layer protocols that deliver data onboard the spacecraft and over the space link;
- Network protocols that provide global addressing and data routing among systems;

- Transport protocols to support end-to-end delivery, and;
- Application protocols to support operational needs.

In the late 1990s, a reference system architecture for the space and ground segments of future IP missions was developed within the OMNI (Operating Missions as Nodes on the Internet) project. The key to this whole architecture is that it is built upon the protocol layering concepts of the ISO OSI network reference model. Based on this research, in February 2000 a standard IP stack was ported to the UoSAT-12 spacecraft developed by Surrey Satellite Technology LTD. (SSTL), England. In April 2000 a series of tests, such as on-orbit testing of UDP telemetry delivery, NTP (operating over UDP) and FTP (operating over TCP), were successfully completed with UoSAT-12 [17].

A further step on space networking beyond UoSAT-12 was seen from Wood et al. [18]. Within the CLEO (Cisco router in Low Earth Orbit) project, a commercial Internet router launched into space in September 2003 onboard the UK-DMC satellite. Until 2008, CLEO has been in orbit for over five years and has been tested in orbit for over four years. CLEO has been powered up for use more than one hundred times. The IPv6 and IPSec have been tested successfully onboard UK-DMC in space. This shows that these additions to the Internet protocol, developed for terrestrial use, can also be used successfully onboard satellites [18], and possibly on fractionated spacecraft.

The work on networking is rarely directly related to the fractionated spacecraft. Ivancic [19] and Wood [20] both discussed the possibility to use existing COTS Internet technology for networking the sub-parts of the fractionated spacecraft. This "mobile-IP" technology has many advantages such as low cost, a large professional knowledge pool, and is extensively tested on a daily basis. One or more (for security) VMOCs (Virtual Mission Operations Center) can be used to allow system operators and users to be remote. The fractionated spacecraft can use routers to form a LAN (Local Area Network) between its own sub-parts while communication with the ground station(s) is performed using WAN (Wide Area Network). DTN (Delay Tolerant Networking) is needed when e.g. parts of large image files are downloaded to different ground stations.

Wireless Communication

The wireless communication for fractionated spacecraft is an extension and synthesis of the technologies of both intra-satellite and inter-satellite communications. As the space wireless

communication itself is already a very broad field, this subsection will only discuss works which have been or will shortly be demonstrated in space.

Intra-satellite wireless communication is an approach to reduce the amount of wiring and to simplify the integration and test. The first intra-satellite communication was realized on space shuttle missions STS-83 and STS-94, both in 1997 [21]. On those mission, 3 Remote Sensor Units (RSUs) were installed on longeron rails in the payload bay and formed a dynamically reconfigurable network. RF tests showed good reception throughout the flight-deck and the mid-deck. Later, on the International Space Station (ISS), a Wireless Instrumentation System (WIS) was installed, which has a 200mW WLAN module working at 900MHz with a data rate of 2Mbit/sec. Next to these examples, a few wireless instruments such as Micro-Strain Gauge Units (MicroSGUs) and Micro-Triaxial Accelerometer Units (MicroTAUs) were also flown on space shuttles.

Although intra-satellite communication tests on space shuttles and the ISS have been successful, so far this technology has not been used on a satellite. The only exception is a very small satellite, Delfi-C³, which was launched in April 2008. Delfi-C³ is equipped with two autonomous wireless sun sensors, each measuring approximately 60mmx40mmx20mm and having a half-sized GaAs solar cell as its own local power supply, making them independent of the satellite's electrical power system [22]. The intra-satellite communication is achieved through a wireless Radio Frequency (RF) link. This link has been made using a modified COTS transceiver operating at 91.5MHz, which enables modularity and flexibility, reduces system mass and volume due to the absence of cables and connectors and is an enabler for "plug and play" construction of satellites. The in orbit experiment demonstrated the feasibility of the wireless link (immunity to disturbances; no interference with other equipment) and the operation of the sun sensor under variable power supply.

Regarding inter-satellite communications, the most famous examples are NASA's Tracking and Data Relay Satellite System (TDRSS), operational since the 1980s, and the Iridium global commercial mobile communication system, launched in 1997 [8]. TDRSS enables spacecraft in any orbit to transfer data forward or backward to other spacecraft or the ground. Iridium allows users on the ground or in the air to communicate with others anywhere on the planet using only a pocket-sized mobile phone. Next to RF communication, the optical communication,

especially laser communication, is very promising due to its relatively low power consumption. Inter-satellite laser communication technology for data relay has been successfully tested in space (see Tab. 1) and will be ready soon on all planned ESA data relay satellites.

Tab. 1 Space Optical Communication Tests

Test Date	Transmitting Satellite	Receiving Satellite	Data Rate
2003	SPOT-4	Artemis	60Mbps
2006	OICETS	Artemis	60Mbps
2008	TerraSAR-X	NFIRE	5.6Gbps

Wireless Power Transfer

Although the physics are identical, wireless power transfer is slightly different from wireless communication: for the prior one, wireless power transfer efficiency is the most important, while for the latter one the signal-to-noise ratio is focused on. Compared with wireless communication, the work on wireless power transfer is still in the infant stage. Even on the ground, wireless power transfer over distances comparable to a few times the diameter of the device has just been realized [23]. For fractionated spacecraft, a far-field power transfer is required to achieve longer distance, often more than 100m due to safety consideration. Therefore, transferring power in space still has a long way to go.

Power transfer via RF, typically in the microwave range, can be made more directional, allowing longer distance power beaming. A rectenna may be used to convert the microwave energy back into electricity with more than 95% conversion efficiency [24]. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth [25], and the beaming of power to interplanetary spacecraft has also been considered [26].

Lafleur and Saleh performed a system-level feasibility assessment of microwave power beaming for small satellites within the fractionated spacecraft context [27, 28]. They utilized parametric models of spacecraft power as a function of 11 design variables, and then found feasible designs through Monte Carlo design trade-space sweeps. Several optimistic assumptions were made, including only two spacecraft or modules in the system, and no pointing losses. Despite these assumptions, it has been found that the design space for power beaming is severely constrained. Feasible designs still require high transmission frequencies, large antenna diameters, and stringent proximity distance. Therefore, Lafleur and Saleh suggested to only consider microwave power beaming as an

auxiliary power mode for small satellite clusters or fractionated spacecraft.

Jamnejad and Silva also investigated microwave power beaming strategies for fractionated spacecraft [29]. Some scenarios have been considered, and various issues, including antenna aperture sizes, separation distances, frequencies and power levels have been discussed. According to the authors, beam shaping can be used to optimize the transmission efficiency while minimizing the interference and power spillover through sidelobes. The utilization of defocusing phase arrays, reflector systems, and reflect arrays is proposed. The authors also suggested several technology investment areas, including efficient rectenna diodes, phased array antennas, high breakdown/low loss transmit filters, phase shifters, and retrodirective systems.

Under a DARPA contract, Turner at Space Systems/Loral studied a new concept for transferring power within a fractionated system [30]. His idea is to use a "mother ship" or Resource Vehicle (RV) with deployable solar arrays to collect solar energy centrally, and then distribute high-intensity beams of unconverted concentrated sunlight to high-temperature compact receivers on "daughter satellites" or Mission Vehicles (MVs) wirelessly. The MVs use heat engines to generate power from heat stored in receiver reservoirs, providing routine and contingency energy storage. According to Turner, the power transfer efficiency of this "concentrated light distribution" scheme is around 25%, much higher than those of microwave (3%) or active optical (4%) schemes. Therefore, this technology is very promising for wireless power transfer in fractionated spacecraft.

Distributed Computing

A distributed computing system may be defined as one in which hardware or software components located at (geographically) different computers communicate and coordinate their actions through a wired or wireless network [31].

Distributed computing onboard a single unmanned spacecraft has been successfully demonstrated in space. The first ever spacecraft utilizing distributed computing were NASA's Voyager 1/2, both launched in 1977, which make use of three RCA 1802 CPUs running at 6.4 MHz [32]. Each concentrates on processing different functions, such as attitude control, data formatting, and commanding. Another NASA spacecraft, the Galileo probe, which was launched in 1989, has dual processors for attitude control and six RCA 1802 Cosmac microprocessor CPUs (four on the spun side and two on the despun

side; each CPU was clocked at about 1.6 MHz, and fabricated on sapphire) in a network for command and data handling [33]. Both spacecraft were designed for long-duration, autonomous flight, a goal difficult to attain without the use of distributed computing.

Townsend et al. [34] and Palmintier et al. [35, 36] designed, implemented and tested a distributed computing architecture for the Emerald nanosatellite formation flying mission. The system is composed of a network of COTS PICmicro® processors linked by a hybrid bus consisting of a high-bandwidth Phillips I²C data bus and a low-bandwidth Dallas Semiconductor "1-wire" microLAN. According to the authors, this system significantly improved the development work of the Emerald satellite. However, it seems that so far this system only works on a single Emerald satellite, although the authors claimed that it could also benefit multi-satellite flight operations.

Distributed computing onboard a cluster of spacecraft has not been realized so far. This is partially due to the complexity of inter-satellite wireless communication and networking, and partially because of the fact that the spacecraft cluster itself is also a relatively new concept. However, limited work has already been done in the context of formation flying and, even for fractionated spacecraft.

Jallad and Vladimirova [37] proposed the deployment of distributed computing on close formation flying missions. Two distributed computing paradigms, named Client-Server and mobile agent, are compared, and eventually the mobile agent paradigm is selected for the application. Meanwhile, in order to evaluate and compare distributed computing paradigms, a real-time testbed was developed, which utilizes LEON-3 processors, the open source SPARC v9 architecture CPU core, and the Real-Time Executive Multi-processor System (RTEMS) operation system. The main contribution of this work is the creation of middleware which is an add-on to the existing Real-Time Operating System (RTOS) and allows tighter coupling between the nodes in the distributed system.

Golding and Wong [38] investigated adaptive distributed computing for fractionated space systems. They regard adaptive distributed computing as multiple distributed applications that all use resources at multiple nodes (spacecraft). The applications have to automatically adapt themselves as needs and resources change. An agent-based architecture is considered for each application. Each agent has a different role and the agents are controlled by a manager. Middleware provides the link between

the agents and the nodes. Each node has predictable resources and services, e.g. compute, storage, communication, sensing, energy. The following problem areas are discussed:

1. *Resource allocation*: how to schedule tasks based on current requirements and resources? A decision algorithm is needed.
2. *Groups and membership*: How to autonomously define an application and how to identify the pieces of an application in a changing environment (spacecraft degrade/are removed/are added)?
3. *Communication*: How to communicate between agents in a secure and reliable manner?
4. *Failure tolerance*: Fault detection/prediction, containment, and recovery are needed as well as dynamic resource allocation. Fault recovery can also mean that a replacement spacecraft is added, preferably as quickly as possible. Failure prediction helps to do that.
5. *Security*: Isolation between nodes and agents is needed to prevent the spreading of malicious software or bugs. The system must be resistant to spoofing, eavesdropping, denial of service, and rogue nodes.
6. *Programming model and tools*: A programming language, API (Application Programming Interface), and development tools need to be developed/selected. A test framework, simulators, and model checkers are also needed.
7. *Standardization and interoperation*: Expect different satellites from different vendors to be added over time. To allow for smooth interoperation, standards need to be defined and rigorously implemented. Also, interoperability tests (testing and formal checks) need to be performed.

All these problems need to be solved before such a scheme can be implemented on fractionated spacecraft.

Fractionated spacecraft Mission

As the fractionated spacecraft is such a new concept, few missions have been proposed based on this revolutionary architecture. So far the only fractionated spacecraft mission that has been announced is Pleiades [39].

The Pleiades system consists of five 225-kg modules (named Atlas-class modules) and two

75-kg modules (named Pleione-class modules), i.e. a total of seven modules. As shown in Tab. 2, the completed Pleiades system will accommodate three Precision Pointing Payloads (PPPs) and a single Coarse Pointing Payload (CPP). These payloads will share two TDRSS transceivers, two Solid State Recorders (SSRs), two high bandwidth downlinks, and two high performance Mission Data Processors (MDPs). The whole system will be launched into orbit in three launches. After each launch, the in-orbit modules will have some capabilities to implement the mission, and after three launches the system will be fully available. Another advantage of using multiple launches is that the most mature sensor can be launched first to allow time for the development of the less mature sensors.

Tab. 2 Pleiades Modules [39].

Launch	1		2			3	
Module	Alcyone	Electra	Maia	Celaeno	Asterop _e	Merope	Taygete
Mass[kg]	225	225	225	75	75	225	225
PPP	Y		Y			Y	
CPP				Y			
TDRSS	Y			Y			
SSR		Y					Y
High BW Downlink		Y					Y
MDP					Y	Y	

At the time LoBosco et al. published their paper, Pleiades was still halfway in the preliminary design.

Summary of the Survey

So far the up-to-date developments in the field of fractionated spacecraft have been reviewed, which covers the architecture, the planned missions, and the four enabling technologies: networking, wireless communication, wireless power transfer and distributed computing.

In the research of fractionated spacecraft architecture, the value-based methodology has already been the mainstream for architecture assessments. There were indeed some doubts about the fractionation, however these negative opinions are more based on qualitative assessments and visibly struggle with their inability to quantify non-traditional attributes such as adaptability and flexibility, which actually are the most important advantages of the fractionated spacecraft. According to the results of value-based assessments, if these non-traditional attributes are considered properly, the benefits brought by flexibility, improved

robustness, and mass production effects will exceed any penalties.

In the field of space networking, exciting progresses have been achieved recently in space. The existing COTS Internet technology developed for terrestrial use, such as commercial Internet router and the standard IP, has been successfully demonstrated onboard satellites. By given a reliable ISL, a very promising solution for fractionated spacecraft networking is to adopt "mobile-IP" technology in space, and use LAN/WAN for inter-module and satellite-ground communications. The DTN could also play a key role for networking between heterogeneous elements due to its capability of overcoming network disconnection. As these technologies have been extensively tested on the ground on a daily basis, they are believed to be ready for space usage soon.

A reliable space wireless communication link is the precondition of realizing other enabling technologies. RF-based inter-satellite communications have already been widely used by TDRSS and Iridium, and the inter-satellite laser communication also has been tested in orbit and will be available for applications within 4 years. The intra-satellite communication is less mature, and only has been demonstrated in orbit recently. However, similar with the networking, the extensive terrestrial applications of the technology of wireless communication will speed up the procedure of space applications.

Wireless power transfer is the biggest challenge among the four enabling technologies. It has just been demonstrated in special environment for terrestrial near-field applications, and the space far-field transfer, which is necessary for fractionated spacecraft, is still in the stage of exploring feasible technical concepts. Although some research indicates that transferring power via RF is not the best choice for fractionated spacecraft, it is still the mainstream and can be improved by using a rectenna to covert the microwave energy back into electricity. Another possible way is to adopt the "concentrated light distribution" scheme for higher power transfer efficiency. However, all these approaches need to be further investigated and tested on the ground before the in-orbit demonstration.

The distributed computing was successfully utilized onboard a single spacecraft many years ago. Its application on a cluster of spacecraft is restrained by the complexity of inter-satellite communication and networking. The agent-based architectures are investigated in the context of fractionated spacecraft. As the agent technology has been demonstrated onboard Deep Space 1, it

can be a very promising solution for distributed computing within a fractionated spacecraft.

Regarding planned missions, so far there is only one demonstration mission announced for fractionated spacecraft. It will be a milestone of the space history; however the details about the utilization of the four enabling technologies in this mission are still not very clear. Especially the technological challenge brought by wireless power transfer is not well addressed, which may be a bottleneck of the whole mission.

Based on the above statements, the results of the survey are partially summarized in Tab. 3, which only covers the four enabling technologies. This assessment was performed according to ESA and NASA's definitions on Technology Readiness Level (TRL).

Tab. 3 Readiness of Enabling Technologies.

Technology	TRL*	Explanation
Networking	5	Partially Demonstrated
Wireless Communication	5	Partially Demonstrated
Wireless Power Transfer	2	Even not used on ground
Distributed Computing	4	Mature for ground applications

* TRL: Technology Readiness Level (ESA&NASA)

SATELLITE R&D ACTIVITIES AT TU DELFT

Satellite research and development activities at TU Delft are centered around the chair of Space Systems Engineering (SSE). The group is particularly focused on engineering of micro- and nano-satellites and distributed space systems. This comprises intra-satellite wireless communication, formation flying missions, and space wireless sensor networks. This section introduces selected aspects which may be considered relevant for fractionated spacecraft.

Delfi-C³

Delfi-C³ is the first Dutch university satellite, which was developed by a group of students in SSE and other chairs in TU Delft with the supervisions from staffs [22]. As shown in Fig. 1, the satellite is a cube with the size of only 100mmX100mmX300mm and the mass of 2.2kg.

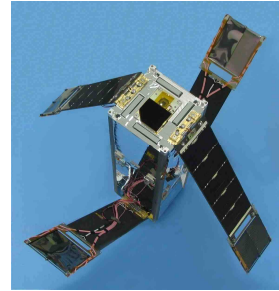


Fig. 1 Delfi-C³ Nanosatellite.

After launched at 28 April 2008 from Sriharikota launching site in India, Delfi-C³ successfully implemented many experiments and is still operational when this paper is published. An important experiment onboard Delfi-C³ is the first ever in-orbit demonstration of autonomous wireless sun sensors. As introduced earlier in this paper, there are two autonomous wireless sun sensors installed on two opposite sides of Delfi-C³. The sun sensors have built-in RF module, which is based a COTS transceiver and can transfer data to the satellite's Command and Data Handling System (CDHS) wirelessly. The success of the demonstration proves that intra-satellite wireless communication can be realized not only on big spacecraft, but also on such a small satellite. After adaption, this technology could also be used for the inter-module wireless communication of fractionated spacecraft.

FAST

FAST (Formation for Atmospheric Science and Technology demonstration) is a cooperative Dutch-Chinese formation flying mission led by TU Delft in the Netherlands and Tsinghua University in China [40]. It is expected to be the first international micro-satellite formation flying mission to achieve objectives in three distinct fields: technology demonstration, earth science and space education. As shown in Fig. 2, in FAST mission, two spacecraft, i.e. FAST-D (being developed in Delft) and FAST-T (under development in Beijing), will demonstrate Autonomous Formation Flying (AFF) using ISL and, furthermore, perform earth observations with more scientific returns due to formation flying.

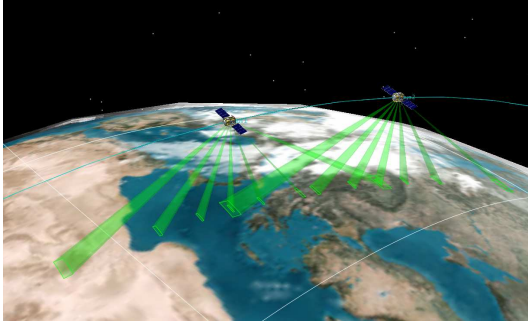


Fig. 2 The FAST Mission.

For the FAST mission, the inter-satellite communication will be realized through a RF-based direct ISL operating at S-band. Meanwhile, space-based distributed computing technique will also be demonstrated by the FAST mission to explore the possibility of fully utilizing the computing powers of AFF small satellites for onboard processing. The concept of space-based distributed computing will utilize the processors on each satellite as a true distributed computer. For the FAST mission this indicates a space-based computer with (at least) two geographically distributed processors. The types of problems under consideration for such a distributed computing network are typically large, dense linear algebra problems. This is because these operations can be processed using blocked algorithms, which are well suited for distributed and, possibly, heterogeneous systems. An important experiment will be the real-time orbit determination of the FAST formation, because the size of this problem could be very large (i.e. thousands of parameters using thousands of observations) and beyond the capability of a single processor [41]. Details about the FAST mission can be found in [42].

Under the framework of the FAST mission, several aspects of formation flying, such as inter-satellite communication, distributed computing, cluster flight, and reconfigurable networking, will be validated, which will also significantly contribute to fractionated spacecraft.

Other Activities

Except the above two projects, SSE is also involved in other activities related to distributed space systems.

One example is the Orbiting Low-Frequency Antennas for Radio Astronomy (OLFAR) project, which presents a new concept of a low frequency radio telescope in space using a cluster of small satellites with the virtual aperture of approximately 100km [43]. As the data correlation must be done in space, distributed processing with centralized downlink transmission is the preferable option, which will bring

challenges to inter-satellite communication, distributed computing, and self-configurable networking.

Another example is the QB50, an international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research [44]. All 50 CubeSats will be launched together on a single launch vehicle into a circular orbit at about 300km altitude, inclination 79°. Although this project aims to use 2unit CubeSats, some technologies such as inter-satellite communication and networking still could be demonstrated.

CONCLUSIONS

As a new sprout in the field of distributed space systems, the concept of fractionated spacecraft is attracting more and more attention. This paper provides a survey of state-of-the-art technologies of fractionated spacecraft which covers six aspects: architecture, networking, wireless communication, wireless power transfer, distributed computing, and the planned missions. The results of the survey, i.e. Tab. 3, **Tab. 3** show that some of the enabling technologies have either been successfully demonstrated in orbit, or already achieved high technical readiness. It is also found that the biggest technical bottleneck for fractionated spacecraft is the wireless power transfer.

This paper also briefly introduces the relevant research and development activities at TU Delft. The successful in-orbit demonstration of intra-satellite wireless communication through the Delfi-C³ nanosatellite, and the planned autonomous formation flying, inter-satellite communication, distributed computing demonstration through the FAST formation flying mission as well as other activities can benefit the development of fractionated spacecraft.

REFERENCES

1. Brown, O. and Eremenko, P., *Fractionated Space Architectures: A Vision for Responsive Space*, Proc. of 4th Responsive Space Conference, AIAA-RS4-2006-1002, Los Angeles, CA, 2006
2. Brown, O., et al., *Cost-Benefit Analysis of a Notional Fractionated SATCOM Architecture*, Proc. of the 24th AIAA International Communications Satellite Systems Conference, AIAA-2006-5328, San Diego, CA, June 11 – 14, 2006
3. Brown, O. and Eremenko, P., *The Value Proposition for Fractionated Space Architectures*, Proc. of AIAA Space 2006

- Conference & Exposition, AIAA-2006-7506, San Jose, CA, September 19-21, 2006
4. Brown O., *Fractionated Spacecraft Workshop: Visions and Objectives*, DARPA Fractionated Spacecraft Workshop, Colorado Springs, August 3-4, 2006
 5. "System F6", Broad Agency Announcement, DARPA, 2007.
http://www.darpa.mil/TTO/solicit/BAA07-31/F6_BAA_Final_07-16-07.doc
 6. "DARPA awards contracts for fractionated spacecraft program".
<http://www.darpa.mil/body/news/2008/F6.pdf>. Retrieved 2009-08-15.
 7. Mathieu, C. and Weigel, A.L., *Assessing the Flexibility Provided by Fractionated Spacecraft*, Proc. of AIAA Space 2005 Conference, AIAA-2005-6700, Long Beach, CA, September 2005
 8. Brown, O., et al., *Fractionated Space Architectures: Tracing the Path to Reality*, Proc. of the 23rd Annual AIAA/USU Conference on Small Satellites, SSC09-I-1, Logan, Utah, US, Aug 10-13, 2009
 9. Molette, P., et al., *Technical and Economical Comparison Between a Modular Geostationary Space Platform and a Cluster of Satellites*, *Acta Astronautica* 12 (11), 1984, pp771-784
 10. Rooney K., *An Exercise in Spacecraft Mission Fractionation*, Presentation, Boeing, August 2006. Retrieved on 2008-09-01.
 11. Mathieu, C. and Weigel, A.L., *Assessing the Flexibility Provided By an On-Orbit Infrastructure of Fractionated Spacecraft*, Proc. of the 56th International Astronautical Congress, IAC-05-D3.3.01, Fukuoka, Japan, October 17-21, 2005
 12. Mathieu C. and Weigel A.L., *Assessing the Fractionated Spacecraft Concept*, Proc. of AIAA SPACE 2006 Conference & Exposition, AIAA-2006-7212, San Jose, CA, September 19-21, 2006
 13. Brown, O., et al., *System Lifecycle Cost Under Uncertainty as a Design Metric Encompassing the Value of Architectural Flexibility*, Proc. of AIAA Space 2007 Conference & Exposition, AIAA-2007-6023, Long Beach, CA, September 18-20, 2007
 14. Brown, A.W., et al., *Software Cost Estimation for Fractionated Space Systems*, Proc. of AIAA SPACE 2008 Conference & Exposition, AIAA-2008-7760, San Diego, CA, September 9-11, 2008
 15. Brown, O. and Eremenko, P., *Application of Value-Centric Design to Space Architectures: The Case of Fractionated Spacecraft*, Proc. of AIAA SPACE 2008 Conference & Exposition, AIAA-2008-7869, San Diego, CA, September 9-11, 2008
 16. Kusza K.L. and Paluszek M.A., *Intersatellite Links: Lower Layer Protocols for Autonomous Constellations*, 1st Joint Space Internet Workshop, Greenbelt, Maryland, USA, November 13-16, 2000
 17. Hogie K., et al., *Using Standard Internet Protocols and Applications in Space*, *Computer Networks*, 47, 2005, pp.603-650
 18. Wood L., et al., *IPv6 and IPSec on a Satellite in Space*, Proc. of the 58th International Astronautical Congress, IAC-07-B2.6.06, Hyderabad, India, September 24-28, 2007
 19. Ivancic W., *Internet Technologies for Space Applications*, DARPA Fractionated Spacecraft Workshop, Colorado Springs, August 3-4, 2006
 20. Wood L., *Data Routing and Transmission Protocols*, DARPA Fractionated Spacecraft Workshop, Colorado Springs, August 3-4, 2006
 21. Kiefer K., *Real-World Experience in Wireless Instrumentation and Control Systems*, CANEUS "Fly-by-Wireless" Workshop, March 27, 2007
 22. Hamann R.J., et al., *Delfi-C3 Preliminary Mission Results*, Proc. Of the 23rd annual AIAA/Utah State University Small Satellite Conference, SSC09-IV-7, Logan, Utah, USA, August 10-13, 2009
 23. "Wireless electricity specification nearing completion". PCWorld. 2009-08-18.
http://www.pcworld.com/article/170360/wireless_electricity_specification_nearing_completion.html?loomia_ow=t0:s0:a41:g2:r18:c0.016236:b27254916:z0. Retrieved 2009-08-20.
 24. Miura T., et al., *Experimental Study of Rectenna Connection for Microwave Power Transmission*, *Electronics and Communications in Japan*, Part 2, Vol. 84, No. 2, 2001
 25. Landis G., *Applications for Space Power by Laser Transmission*, SPIE Optics, Electro-optics & Laser Conference, Los Angeles CA, January 24-28 1994
 26. Landis G., et al., *Space Transfer With Ground-Based Laser/Electric Propulsion*, Proc. of the 28th SAE, ASME, and ASEE

- Joint Propulsion Conference and Exhibit,
AIAA-92-3213, Nashville, TN, July 6-8,
1992
27. Lafleur J.M. and Saleh J.H., *Feasibility Assessment of Microwave Power Beaming for Small Satellites*, Proc. of the 6th International Energy Conversion Engineering Conference, AIAA 2008-5714, Cleveland, OH, July 28-30, 2008
 28. Lafleur J.M. and Saleh J.H., *System-Level Feasibility Assessment of Microwave Power Beaming for Small Satellites*, Journal of Propulsion and Power, vol.25 no.4, 2009, pp976-983
 29. Jamnejad V. and Silva A., *Microwave Power Beaming Strategies for Fractionated Spacecraft Systems*, Proc. of the 2008 IEEE Aerospace Conference, Big Sky, MT, March 1-8, 2008
 30. Turner A.E., *Power Transfer for Formation Flying Spacecraft*, Proc. of AIAA SPACE 2006 Conference & Exposition, AIAA-2006-7493, San Jose, CA, September 19-21, 2006
 31. Coulouris G., et al., *Distributed Systems: Concepts and Design*, 4th Edition, Addison Wesley/Pearson Education, June 2005
 32. Tomayko J.E., *Computers in Spaceflight: The NASA Experience*, NASA Contractor Report 182505, March 1988
 33. Meltzer M., *Mission to Jupiter: a History of the Galileo Project*, NASA SP 2007-4231, NASA, 2007
 34. Townsend J., et al., *Effects of a Distributed Computing Architecture on the Emerald Nanosatellite Development Process*, Proc. of the 14th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August, 2000.
 35. Palmintier B., et al., *Distributed Computing on Emerald: A modular approach for Robust Distributed Space Systems*, Proc. of the 2000 IEEE Aerospace Conference, Big Sky, MT, March 2000.
 36. Palmintier B., et al., *A Distributed Computing Architecture for Small Satellite and Multi-Spacecraft Missions*, Proc. of the 16th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August, 2002.
 37. Jallad A.H. and Vladimirova T., *Distributed Computing for Formation Flying Missions*, Proceedings of the 2006 IEEE/ACS International Conference on Computer Systems and Applications, Dubai/Sharjah, UAE, March 8-11, 2006
 38. Golding R., Wong T., *Adaptive distributed computing for fractionated space systems*, DARPA Fractionated Spacecraft Workshop, Colorado Springs, August 3-4, 2006
 39. LoBosco, D.M., et al., *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, 9-11 September 2008
 40. Maessen, D.C., et al., *Preliminary Design of the Dutch-Chinese FAST Micro-Satellite Mission*, Proc. of the 45 Symposium, Rhodes, Greece, May 26-30, 2008
 41. Maessen D.C., et al., *Increasing System Performance and Flexibility: Distributed Computing and Routing of Data within the FAST Formation Flying Mission*, Proc. of the 59th International Astronautics Congress, IAC-08-D1.4.6, Glasgow, Scotland, September 29 – October 3, 2008
 42. Guo J., et al., *Status of the Fast Mission: Micro-Satellite Formation Flying For Technology, Science and Education*, Proc. of the 60th International Astronautical Congress, IAC-09-B4.2.5, Daejeon, Korea, October 12-16, 2009
 43. Bentum M.J., et al., *A Novel Astronomical Application for Formation Flying of Miniaturized Satellites*, Proc. of the 60th International Astronautical Congress, IAC-09-A3.4.3, Daejeon, Korea, October 12-16, 2009
 44. Muylaert J., et al., *QB50: An International Network of 50 CubeSats in LEO for Lower Thermosphere and Re-Entry Research*, The 23rd Annual Conference on Small Satellites, CubeSats Developer's Workshop, Logan, UT, USA, August 8-9th, 2009