Fractionation and Implications for Flexible Space System Design

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Biography

Greg Lack is pursuing his S.M. in the Department of Aeronautics and Astronautics. In May of 2007 he completed a B.S. in Aerospace Engineering at Syracuse University. His present academic and research endeavors focus on the design of flexible space systems, and fractionated space system architectures. In his research he places a particular emphasis on the use of economics for (space) system design, and decision making in system design.

Related Publications

Brown, Owen, and Paul Eremenko. "The Value Proposition for Fractionated Space Architectures." *AIAA Space 2006 Conference and Exposition.* San Jose, California: AIAA 2006-7506.

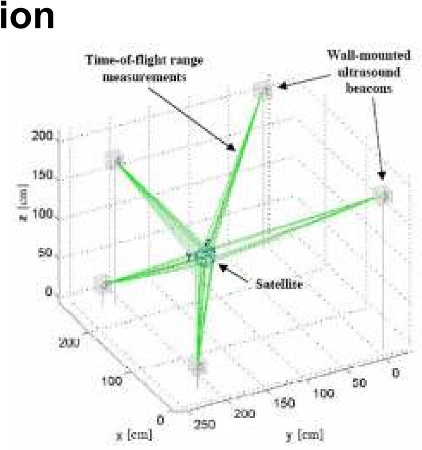
Mathieu, C., and Annalisa Weigel. "Assessing the Fractionated Spacecraft Concept." *AIAA Space 2006 Conference and Exposition.* San Jose, California: AIAA 2006-7212.

1 Fractionated Space System Design

- **Fractionation**
  - A fractionated space system consists of a set of modules that collaborate on-orbit to achieve a certain level of system functionality.
  - 3 possible levels of fractionation:
    - Mission Architecture Level
    - Space System Level
    - Subsystem Level
  - 2 classifications of fractionated space systems:
    - Homogeneous
    - Heterogeneous

A Fractionated Space System
Image Credit: *DARPA, Dr. Owen Brown*

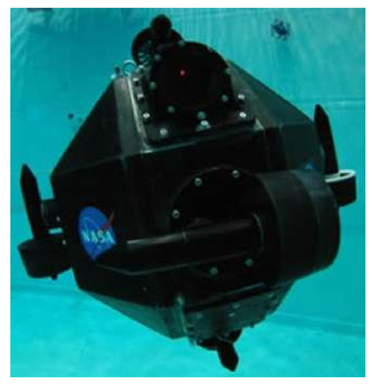
- **Enabling Technologies (Key Challenges) for Fractionation**
  - Distributed Power Systems
    - AC/DC power cables, electromagnetic inductive coupling, radio-frequency or laser beamed power
  - Distributed Station-keeping
    - Reaction wheels and electromagnets
  - Relative Navigation
    - Global Metrology (MIT), IMU & VPS (U. Maryland)
  - Distributed Payload Systems
  - Distributed Computing Systems
  - Wireless Information Transfer
    - Omni-directional or directional antennas



The Global Metrology Concept
Image Credit: *SPHERES, Mehdi Alighanbari*

2 Fractionation in Practice

- **Academics**
  - University Nanosatellite Program (UNP)
    - Began in 1999, managed by the AFRL - have held 5, 2-year competitions to date
    - Has lead to the full-scale development of nanosats that demonstrate key fractionated technologies
  - Synchronize Position Hold Engage and Reorient Experimental Satellites (SPHERES) - MIT
    - Focus is on 'Global Metrology' autonomous relative navigation system
    - 7 successful tests of the SPHERES onboard the ISS to date
  - Secondary Camera And Maneuvering Platform (SCAMP) – U.M.
    - Focus is on IMU & VPS autonomous relative navigation system
    - Testing has only been done in a neutral buoyancy environment
- **Government and the Space Systems Industry**
  - Space Technology 5 (ST5)
    - NASA - 3 satellites demonstrated formation flying
  - Cluster II
    - EAS & NASA - 4 satellites demonstrated formation flying
  - Atmospheric Neutral Density Experiment (ANDE)
    - NRL – 2 satellites that demonstrated cluster flying
  - Technology Satellite 21 (TechSat-21)
    - AFRL – 3 satellites designed to demonstrate autonomous formation flying but were never launched
  - Exoplanet Exploration Program (ExEP)
    - NASA – Terrestrial Planet Finder flying formation Interferometer (TPF-I)
  - DARPA F6 Program
    - DARPA – leading initiative for the development of fractionated system design methodologies



SCAMP
Image Credit: *University of Maryland, Space Systems Laboratory*

3 Fractionated Space Systems: Motivation

- **Modularity** (fractionated systems are inherently modular)
  - A modular system can be decomposed into a set of distinct *modules* that can be designed, tested, and manufactured independently. These modules can then be easily integrated to form a system.
  - Modular systems can potentially lead to:
    - More efficiency in the design and development of a system
    - A reduced need to maintain a diverse workforce
    - Increased innovation in a system design
    - More effective/successful design of complex systems
  - Modular Evolution and its Implications
    - **Computers (1941 – present):** 109,738% to 2% decrease in the cost of a computer relative to the average salary of a laborer.
    - **Automotive (1885 - present):** 121% to 44% decrease in the cost of an automobile relative to the average salary of a laborer.

The IBM System/360 (circa 1964)
Image Credit: *Adam Rosenberg*

- **Managing Uncertainty via System Flexibility** (fractionated systems are inherently flexible)
  - Market Supply & Demand: system demand, requirement, and supply fluctuations
  - National Security: potential, unknown external threats to a system
  - Technical: hardware and software reliability issues, possibility of on-orbit failure
  - Environmental: uncertainty of a systems operating environment
  - Funding: change in system funding, or allocation of funding
  - Launch: launch system reliability, schedule slip, etc.
  - Programmatic: change in a system's development/project schedule, delays, etc.
- **How can we design space systems that are *flexible*?**

4 Design for Flexibility Methods

- **Design for Flexibility Methods enable system designers to design flexible systems.**
  - Design for Flexibility Method: A design methodology that does one or more of the following:
    - ***Identify*** the most valuable locations in a system to embed flexibility
    - ***Quantify*** the specific level of flexibility in a system
    - ***Value*** flexibility in terms of the monetary gain resulting from embedding flexibility
- **Literature Review: Design for Flexibility Methods**
  - Dynamic Multi-Attribute Tradespace Exploration (Dynamic MATE) – Adam Ross
  - Engineering Systems Matrix – Jason Bartolomei
  - Real Options Analysis – Fischer Black, Myron Scholes, Robert Merton, and Stewart Myers
  - Real Options "In" Analysis – Richard de Neufville, and Tao Wang
  - Generalized Information Network Analysis (GINA) – Graeme Shaw
  - Change Propagation Analysis (CPA) – Claudia Eckert, John Clarkson, and Winfried Zanker
  - Decision Analysis – Roger Pye
  - Architecting Options – Avner Engel, and Tyson Browning
  - Time-Expanded Decision Network – Matthew Silver, and Oliver de Weck
  - 6E Flexibility Framework – Roshanak Nilchiani, and Daniel Hastings
  - Decision-Based Design Framework (DBD) – Andrew Olewnik, and Lewis Kemper
  - Flexible Design Methodology – Chrisoph Roser, and David Kazmer
  - Flexible Product Platform Design Process – Eun Suh
- **Why would a system designer want to design flexible systems?**

5 Designing Flexible Systems: Motivation

- **Synthesis of Flexibility**
  - Based on the Design for Flexibility Methods respective *Definitions* for flexibility

Design for Flexibility	Context of Flexibility	Name(s) for Flexibility	Action Enabled by Flexibility	Motivation for the Action	Context in which the Action Occurs	Result of the Action (physical impact)	Objective of Incorporating Flexibility
Time-Expanded Decision Network	property of a system	flexibility	adapt	(1) changes in operational environment; (2) uncertain operational environments	over a period of time	change in system capabilities	(1) manage a complex system in the face of uncertainty; (2) create systems that are effective in the long-

  - Based on the Design for Flexibility Methods respective *Processes* for designing flexible

Design for Flexibility	System Set	Flexibility and the System Set	Identify Flexibility	Quantify Flexibility	Value Flexibility	How Uncertainty is Modeled	(Actual) Model Outputs	Socio-Technical Considerations
Time-Expanded Decision Network	A (small) set of candidate system designs	Switching between those candidate system designs	Yes	No	No	introducing operational and demand scenarios into the computation of LCC for a candidate	LCC of each candidate system design, and the LCC of alternative (flexible) candidate	Operational and demand scenarios introduced in the LCC computations

- **Synthesized Definition of Flexibility**
  - Flexibility is a property of a system that allows it to maintain value delivery by changing the capabilities of the system in response to uncertain operational environments (endogenous and exogenous to the system). Specifically, the uncertainty in the operational environments results from potential changes in the system's initial objectives, requirements, and preferences for the system.
  - Flexibility is not synonymous to robustness.

#	The Essence of Flexibility
1	Maintain System Capability/Functionality/Service Delivery
2	Maintain System Value Delivery
3	Improve System Operational Effectiveness
4	Improve System Technical Effectiveness
5	Improve System Programmatic Effectiveness
6	Manage Uncertainty in a System's Operational Environment
7	Increase or Ensure System Reliability
8	Allow for Informed Decisions to be made about a System
9	Increase or Ensure System Robustness
10	Enable the System to Take Advantage of Emergent Opportunities
11	Aid in Investment Decision Making Regarding the System
12	Aid in Business Planning for the System
13	Allow for the Creation of Multi-Mission Capable Systems
14	Allow for the Creation of Effective, Long-Term Systems
15	Allow for the Addition New System Application(s)
16	Reduce the Technological Obsolescence in a System
17	Allow for the Effective Management of Risks
18	Allow for the Creation of a Dynamically Responsive System
19	Allow for the Creation of System Redundancy
20	Allow for a Changeable System
21	Allow for Valuable and Efficient Socio-Technical Systems

6 Conclusions and Future Work

- **Conclusions**
  - Fractionated Space Systems
    - There is a growing interest in fractionated space system design.
    - Fractionated space systems are inherently flexible and modular.
    - There are many key technologies that still need to be developed to make fractionation a reality.
  - Design for Flexibility Methods
    - There have been numerous methods developed that can be used to design for flexibility.
  - Flexibility
    - The essence of flexibility serves as a source of motivation for system designers to embed flexibility into a system design (i.e. design for flexibility).
- **Future Work**
  - Define a Thesis Topic (potentially based on the following research questions):
    - How do we make the notion of system flexibility more tangible to system stakeholders such that they are more inclined to value systems based on their respective flexibility rather than their costs?
    - What are the implications of flexibility for different classes of space systems?
    - What are the implications of flexibility for different types of missions?
    - What are the key drivers that determine the "best" number of modules to fractionate a monolith into?
    - What are the principal sources of value for a fractionated system? What portions of the net value are traceable to changes in cost, flexibility, robustness, etc.?
    - What are the principal drivers of risk in a monolithic system? An "optimal" fractionated counterpart?
    - How would the optimal fractionated system differ for a risk-averse vs. a risk seeking stakeholder?

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