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The Development of Dynamic Guidance and Navigation Algorithms for Autonomous On-Orbit Multi-Satellite Aggregation

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The Current State of Space System Morphology

Despite the exciting, dynamic expansion of space exploration and technology, two major facts remain:

1. Size, mass, and power of space systems remain proportional to cost and performance.

2. Today's spacecraft still resemble monolithic structures like those from 50 years ago.

Mariner 4
1964
Mars Flyby [1]

GOES-8
1994
Meteorology [2]

Aeneas
2012
CubeSat [3]

Hayabusa2
2014
Asteroid Sample Return [4]

Iridium Next
2017
Communications Constellation
[5]

What if there were a way to decrease the overall costs of a space system while maintaining overall performance? What would a potential solution look like?

Hint: it could involve many smaller satellites!

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Two New Focus Areas

Swarm / Constellations

- Using many similar monolithic satellites in particular orbits to achieve mission objectives.

- Increases capabilities in performing traditional applications like remote sensing, communications, etc.

- Expand upon system performance (compared to a single spacecraft), but doesn't necessary decrease costs.

On-orbit Aggregation

- Using lower cost "building blocks" to physically build large assemblies.

- Introduces new possible applications like refueling, on-orbit servicing, etc.

- Maintain or expand upon system performance (compared to a single spacecraft) while decreasing mission costs.

We focus our efforts on exploring the possibilities of **on-orbit aggregation** through a biologically-inspired ideology called "cellularization."

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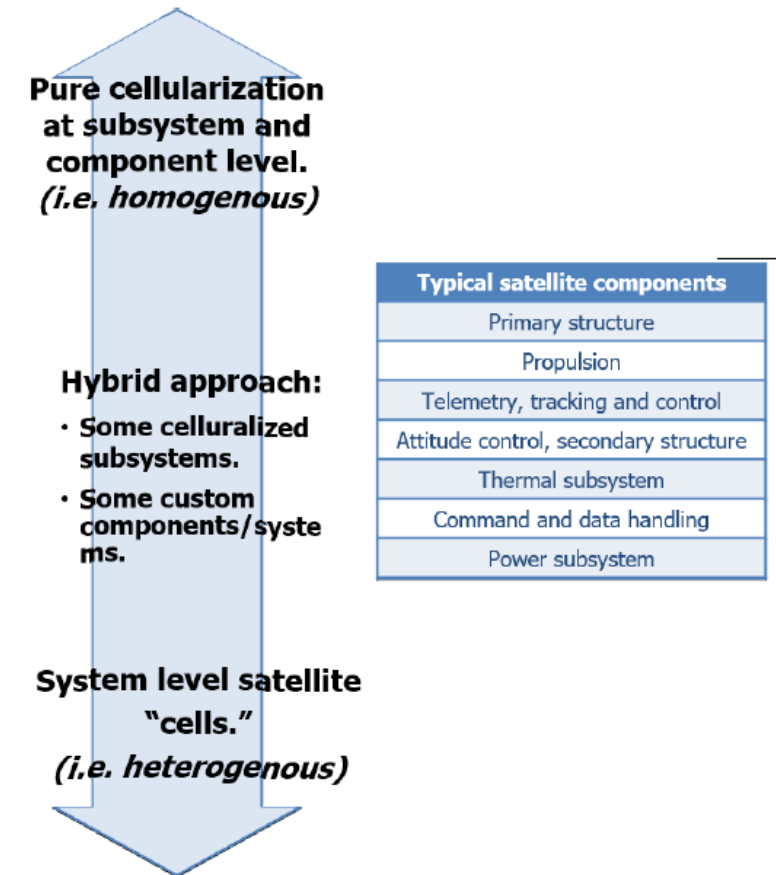# Focus on Cellular Morphology to Enable On-orbit Aggregation

Proposed solution: Applying concepts of "cellularization" to spacecraft design and on-orbit aggregation to construct large-scale space systems.

"Cellularization" is the idea that many small cells may form larger functioning specializations. Applying this to space systems, we can redefine "system-level" satellite "cells" and a "component-level" element for satellite subsystems.

Ultimately, aggregation should be able to occur between system-level and/or component-level interfaces (homogeneous and/or heterogenous).

How can we ensure seamless integration and functionality across N-number of aggregate components?

Answer: **To enable true aggregation, a sophisticated aggregation architecture is required to combine both software and hardware layers across different levels of homo/heterogeneity.**

Pure cellularization at subsystem and component level.
(i.e. homogenous)

Hybrid approach:
- Some cellularized subsystems.
- Some custom components/systems.

System level satellite "cells."
(i.e. heterogenous)

Typical satellite components
Primary structure
Propulsion
Telemetry, tracking and control
Attitude control, secondary structure
Thermal subsystem
Command and data handling
Power subsystem

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# A Proposed Aggregation Architecture

Architecture Layers

1. **Software** – lowest layer that characterizes component-level needs/capabilities

2. **Hardware** – consideration of physical aggregation of elements (IMU, processors, etc.)

3. **Data Transport** – wireless protocol that enables information flow

4. **Hardware Resource Transport** – account of needs/capabilities of physical hardware elements

5. **System Aggregation Behavior** – application of software to ensure that aggregate system performs as a monolithic entity (e.g., maintaining system's isothermal condition).
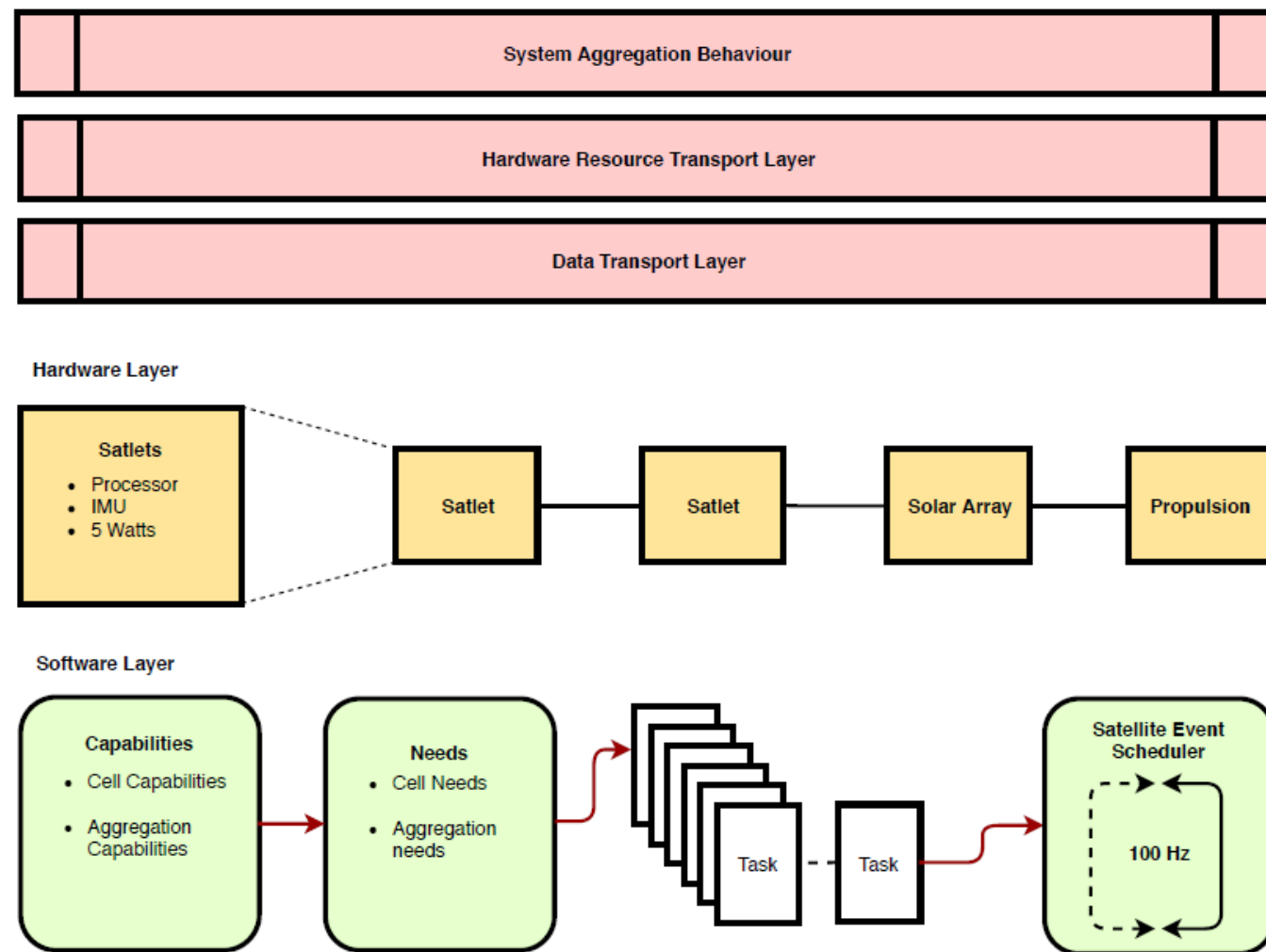
System Aggregation Behavior: GNC

Ultimately, an aggregate space system must still adhere to traditional spacecraft design considerations (**system aggregation behavior**). More specifically, we focus on the GNC subsystem due to its high impact on other major subsystems (power, communications, thermal, payload, etc.).

When aggregating many "cellular" elements, the resulting space system undergoes changes in mass properties (center of mass, moments of inertia) and vehicle dynamics. Careful consideration must be made to account for new control requirements (e.g., to avoid thruster misalignment and undesired resultant outputs).
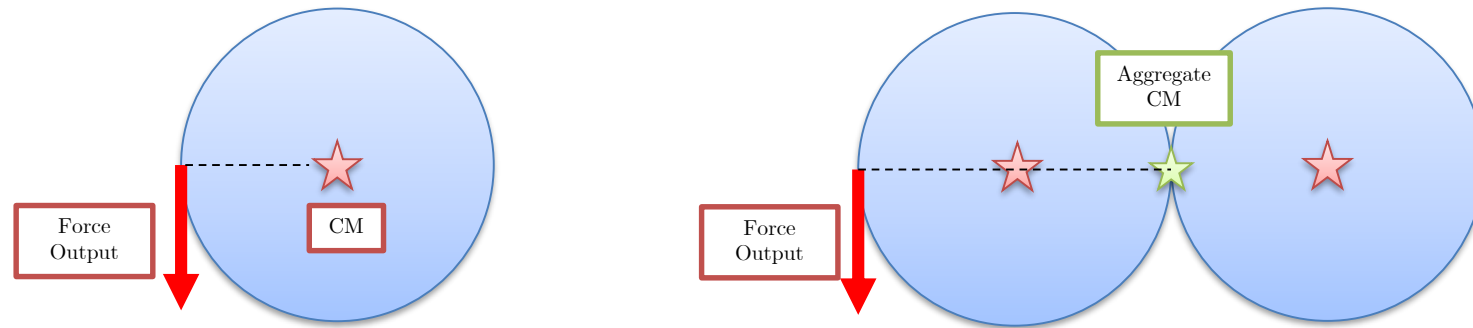

Therefore, an aggregate system must possess the capability of autonomous reconfiguration of any number of elements!

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A Demonstration of Aggregation Behavior

To demonstrate the viability of the reconfiguration algorithm through hardware, we fabricate cellular spacecraft prototypes, called Satbots, which emulate 3DOF orbit operations.

Each Satbot possesses a simple 8-thruster GNC system, navigational sensor, and onboard processor to perform GNC operations.

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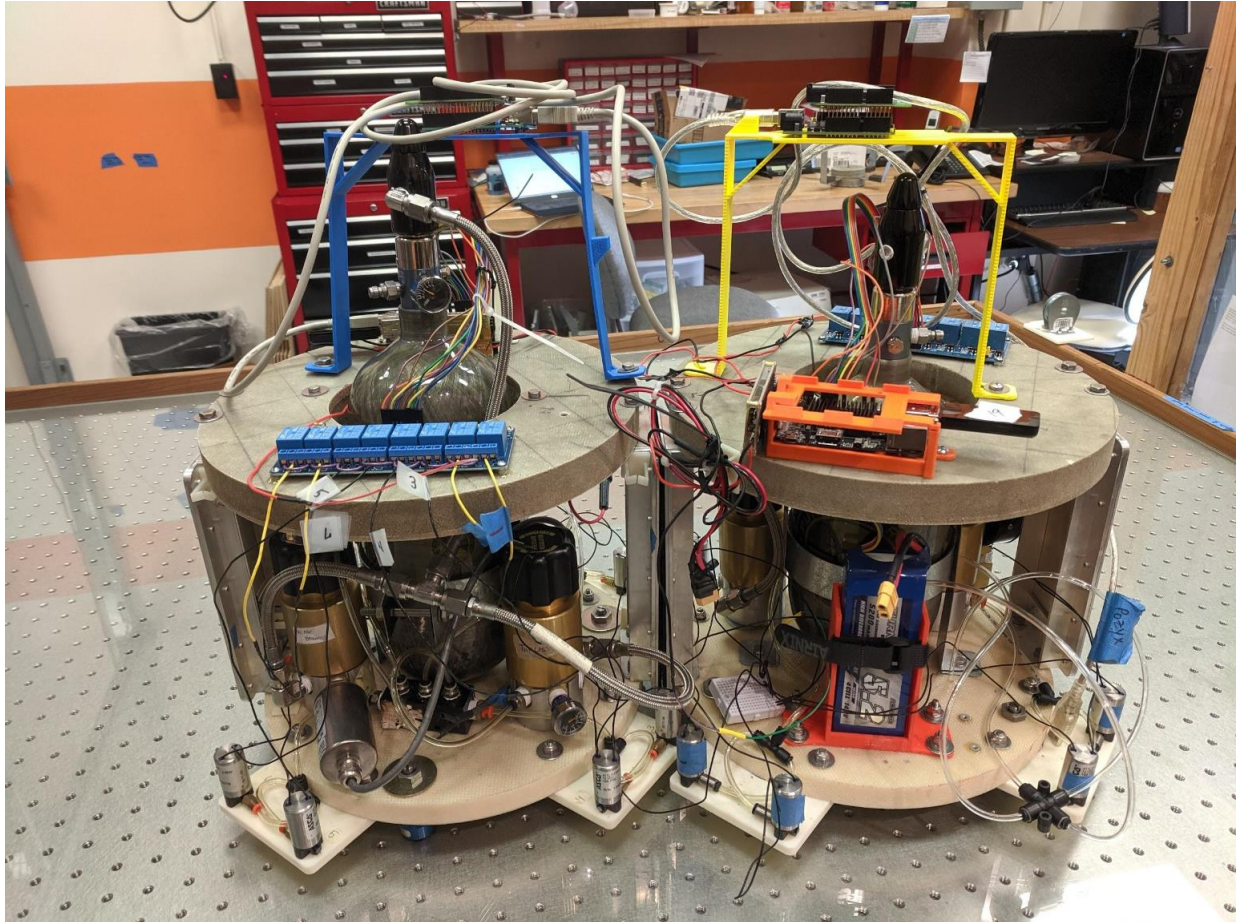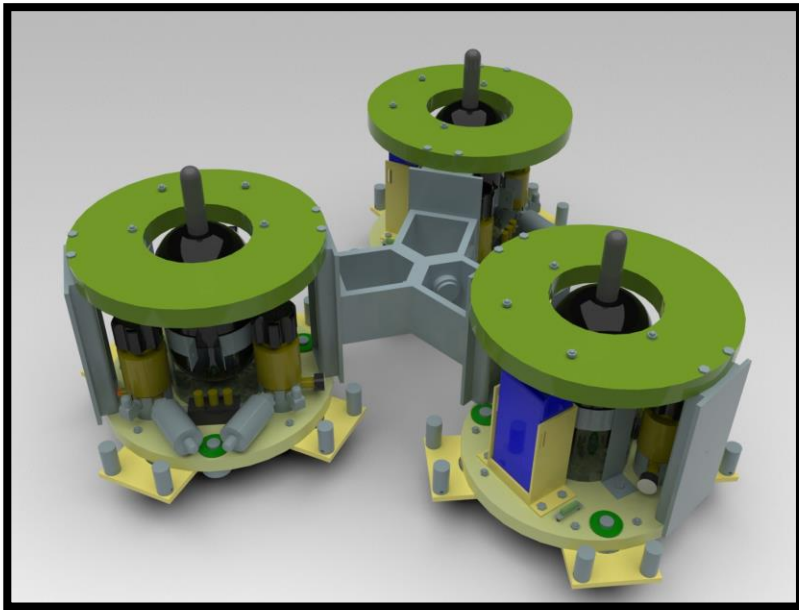
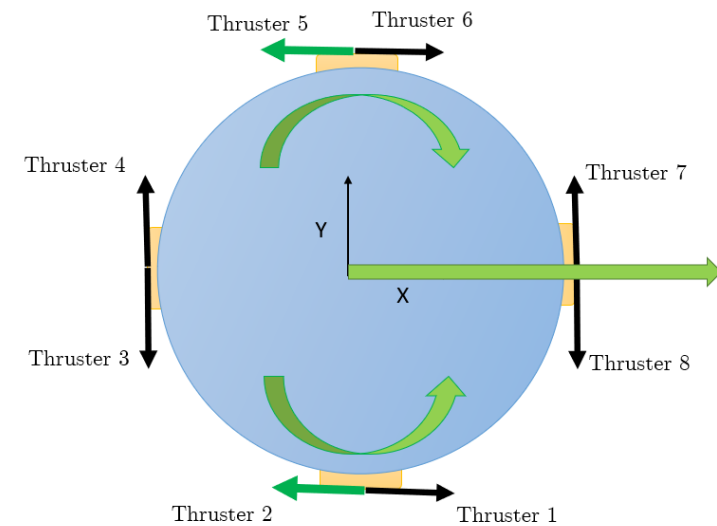# Proposed GNC Operations for an Aggregate Satbot System

1. Each Satbot identifies a desired state.

2. Each Satbot performs GNC operations to propel towards its destination.

3. Satbots identify if aggregation has occurred.

4. Each Satbot uploads its "ID" file of GNC hardware parameters through the proposed data transport layer.

5. An aggregate "ID" file is created and distributed to *one random Satbot.*

6. The reconfiguration algorithm calculates the control for the aggregate system.

7. Each Satbot's control responsibilities are distributed accordingly.

8. GNC operations continue.

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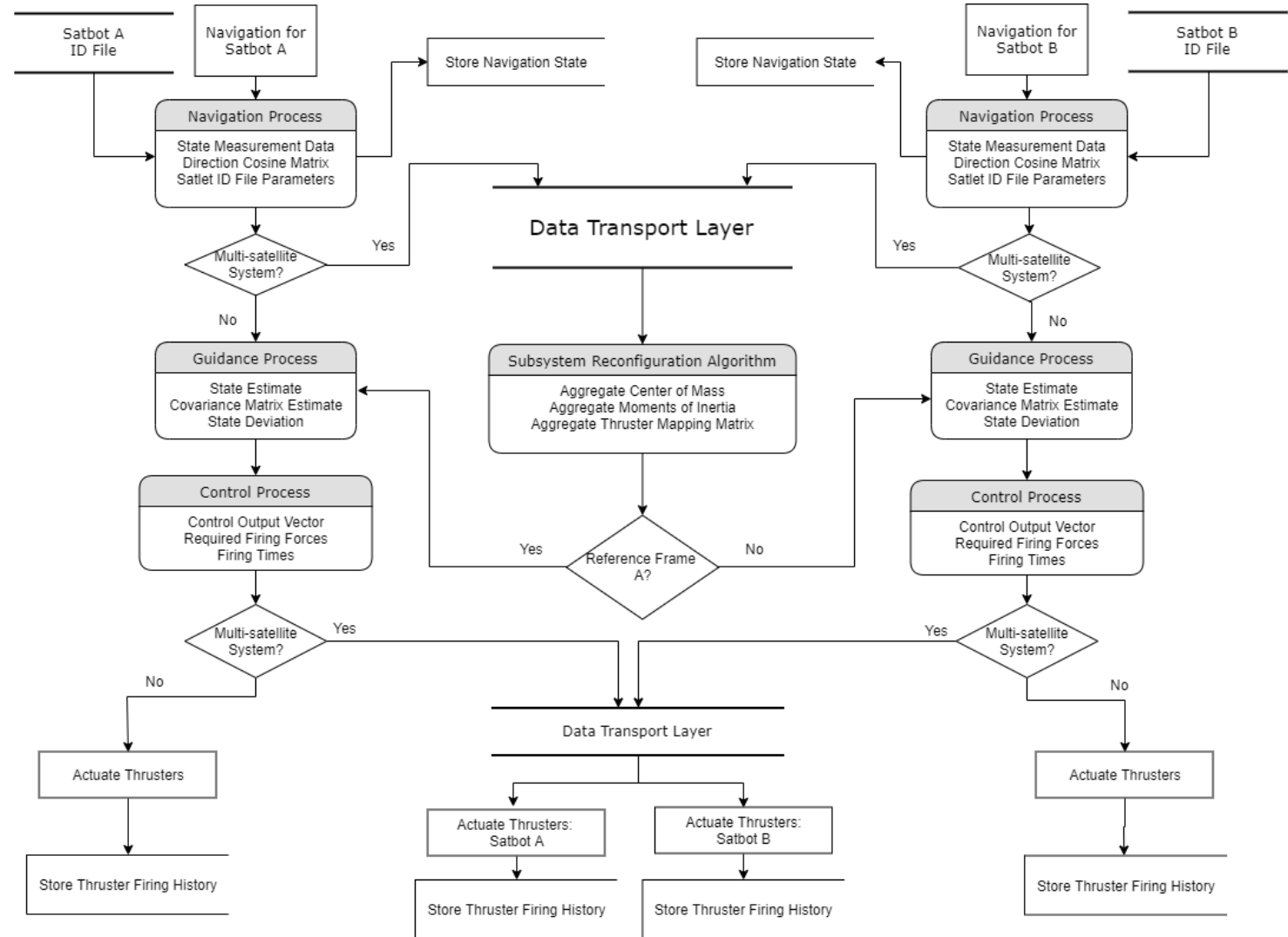
GNC Reconfiguration Development

We implement a **scalable** thruster mapping matrix to support the early stages of autonomous control; this links physical hardware capabilities with the Satbot's properties. With this matrix, the Satbot understands which thruster contributes what control output.

Example: If the Satbot must move forward in the +X-direction, then thrusters 2 & 5 actuate to provide the necessary force.

	Resultant Force Direction		Resultant Torque Direction
Thruster	X	Y	Z
1	-1	0	-τ
2	+1	0	+τ
3	0	+1	-τ
4	0	-1	+τ
5	+1	0	-τ
6	-1	0	+τ
7	0	-1	-τ
8	0	+1	+τ

u – Control Output
M – Mapping Matrix
f – firing forces for each thruster

$$u = Mf$$

$$\begin{bmatrix} f_x \\ f_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & -1 & 1 \\ -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \end{bmatrix}$$

$$f = 2\,M^+ u$$

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \end{bmatrix} = \begin{bmatrix} -0.5 & 0 & -0.25 \\ 0.5 & 0 & 0.25 \\ 0 & 0.5 & -0.25 \\ 0 & -0.5 & 0.25 \\ 0.5 & 0 & -0.25 \\ -0.5 & 0 & 0.25 \\ 0 & -0.5 & -0.25 \\ 0 & 0.5 & 0.25 \end{bmatrix} \begin{bmatrix} f_x \\ f_y \\ \tau_z \end{bmatrix}$$

Upon aggregation, the thruster mapping matrix changes accordingly, and the aggregate matrix is distributed throughout every Satbot to maintain proper control.

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GNC Reconfiguration Demonstration Results

Current testing of the reconfiguration of the GNC hardware of 2 Satbots shows promising preliminary results. The aggregate system was able to calculate the required control contributions from different thruster systems and actuate accordingly.

The next steps consist of:

- Improving the precision and autonomy of the GNC operation.
- Developing more functionality of the proposed aggregation architecture.
- Fabricating more lightweight Satbot prototypes.

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Applications

Combining the concept of cellularization with the proposed computational architecture will enable the means to assemble smaller platforms on-orbit to achieve mission objectives.

Mastering these capabilities will enable a new realm of space system design with endless possibilities and applications like:

- On-orbit servicing, like refueling or replacing components.
- Constructing complex, large-scale projects, like space telescopes or space stations.

Example art of spacecraft refueling [6]
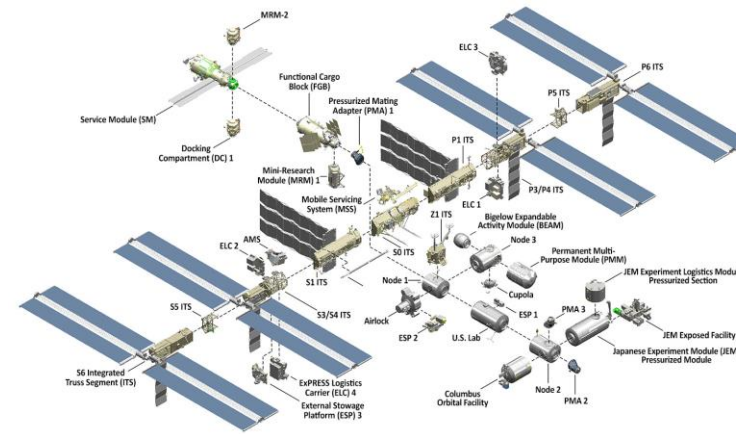
ISS breakdown of components [7]

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Conclusion

We currently research the means to expand the capabilities of future space systems by exploring an innovative "cellular" morphology.

- Concepts of cellularization and on-orbit aggregation of space systems shows promise in reducing costs while maintain system performance.

- A notional computational architecture introduces the framework that is necessary to accommodate true multi-satellite aggregation.

- We focus on demonstrating the aggregate system behavior of the architecture through the reconfiguring of GNC hardware on a simple cellular prototype

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QUESTIONS

Picture References

[1] Reiff, G. A. (n.d.). Mariner 4. Retrieved from https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1964-077A.

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[4] JAXA. (n.d.). Hayabusa2. Retrieved from https://solarsystem.nasa.gov/missions/hayabusa-2/in-depth/.

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[7] Reference Guide To the International Space Station. (n.d.). Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/np-2015-05-022-jsc-iss-guide-2015-update-111015-508c.pdf.

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