Design and Testing of Clustered Components for Modular Spacecraft Architectures

Admission to the final exam

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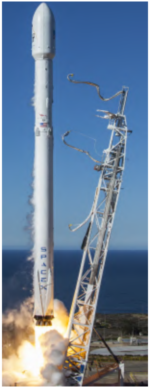
Clusters are not new

Clusters have always been used to improve reliability

The results contained in this work can be applied directly to systems which feature clusters by design.

However, new architectures enable new types of clusters

An evolution of spacecraft concepts

Figure: Monolithic Architecture

Figure: Fractionated Concept

Figure: Federated Concept

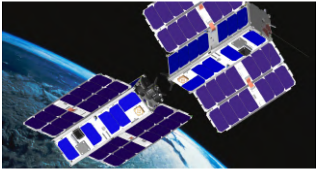


Figure: In orbit assembly

Monolithic $\rightarrow$ Fractionated $\rightarrow$ Federated Vs In orbit assembly

Virtual clusters

Multi agent concepts feature a lot of redundancy

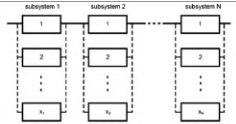
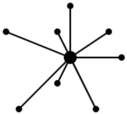
We can imagine a *virtual cluster* as the collection of **similar subsystems spread across multiple spacecraft**

Compared with traditional clusters, *virtual* ones have different requirements and objectives; in particular they must consider **dynamic architectures**

In this work, we study cluster under two lenses:

- Operational phase: $\Rightarrow$ How to control virtual and traditional clusters effectively
- Design phase: $\Rightarrow$ How to exploit cluster proprieties during system design

Part I: Reliability Vs Performance

Architecture	Reliability	Performance
	Good	As good as the individual component
	Failure modes **not independent** (worst case: single point of failure)	Good

Coordination may weaken the independent failure hypothesis.

Can we have **both reliability and performance**?

Statement of the control problem

Can we maintains failure probabilities independent and yet optimize efficiency ?

We use a decentralized algorithm and forbid communication among the agents

Bonus: this bounds operational complexity and enhances scaling.

In some cases **Dual Ascent** (a classical solutions for decentralized control) can be implemented without direct communication between the agents

Proposed Method

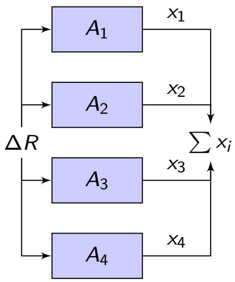


Figure: Cluster of 4 generic agents

Assumptions

- Single Input - Single Output Agents
- No communication allowed
- Agent i produces an output x_i according to an agreed upon rule

Algorithm:

1. Measure the global propriety ΔR
2. Compute $x_i|_{t_{s+1}}$ according to Eq. 1

$$x_i|_{t_{s+1}} = x_i|_{t_s} + k \cdot \Delta R + \frac{\partial \varepsilon}{\partial x_i} \qquad (1)$$

3. Repeat

Analytical results

We provide proof that the proposed algorithm converges to a local constrained optima, provided that the tuning variable k is chosen large enough.

Contrary to Dual Ascent, it requires no hypothesis on the convexity of the cost function.

Typical dynamic can be viewed in two phases:

1. Quickly meets the constraint
2. Slowly moves along the constraint toward the optima

Bonus: It is very simple to implement

An Application to Small Satellites

To compare and characterize performance, we consider a Reaction Wheel

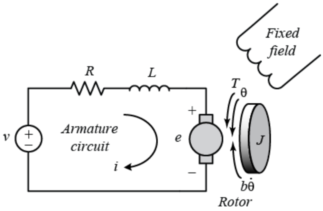


Figure: The standard electro-mechanical model for a DC engine

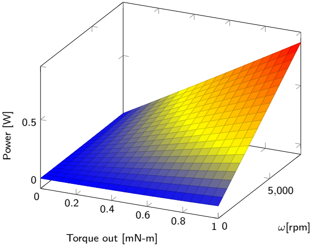


Figure: Power required for a given T and ω (analytical model)

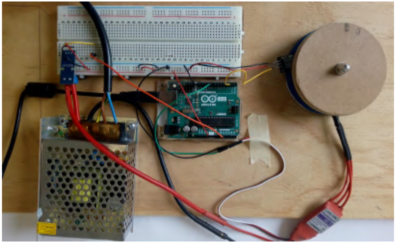
We can derive power consumption analytically:

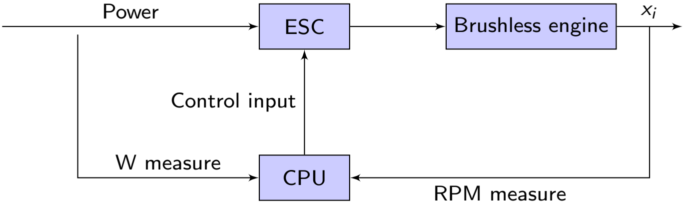
$$P_{el}(T_{out}, \omega) = T_{out}^2 \frac{R}{k_t^2} + T_{out} \cdot \left(2B \frac{R}{k_t^2} + \frac{k_v}{k_t} \right) \omega + B \left(\frac{BR}{k_t^2} + \frac{k_v}{k_t} \right) \omega^2 \qquad (2)$$

We need to estimate the motor coefficients B, k_t, R

Hardware overview

An hardware prototype is used to fit the analytical model





Closed Loop Characterization

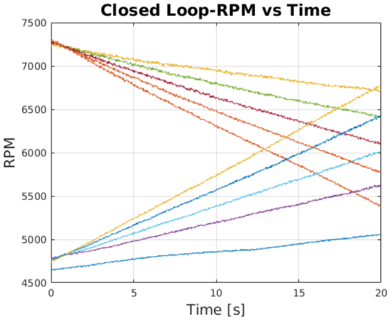


Figure: RPM over time: Reading from various angular acceleration requests (increasing and decreasing)

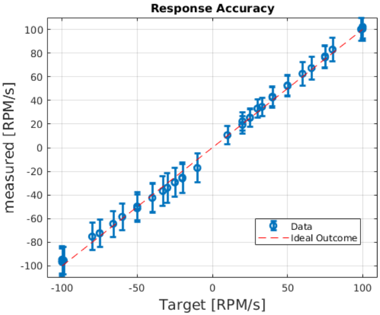


Figure: Request Vs output; measured angular acceleration is averaged over a signal of approximately 20 seconds

Power consumption model

Direct fit (using the analytical model); convex with $\dot{\omega}$ request

$$P|_{\mathrm{W}}(\omega|_{\mathrm{RPM}}, \dot{\omega}|_{\mathrm{RPM/s}}) = a \cdot \dot{\omega}^2 + b\omega^2 + \dot{\omega} c\omega + d \tag{3}$$

Accuracy is poor ($\mathrm{R}^2 = 82.3\%$)

Fitting an empirical model provides better results ($\mathrm{R}^2 = 99\%$)

$$P|_{\mathrm{W}}(\omega|_{\mathrm{RPM}}, \dot{\omega}|_{\mathrm{RPM/s}}) = a \cdot \dot{\omega} + b\omega^2 + c\omega + d \tag{4}$$

However, the second model is **linear with torque** so Dual Ascent does not work.

Efficiency comparison

We compare power consumption using either the Proposed Methods (PM) or Static Allocation (SA), for different cluster sizes.

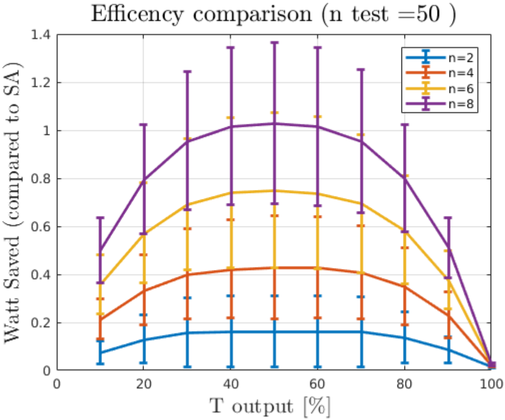


Figure: Average power consumption improvement over multiple tests, initialized with randomly selected $\vec{\omega}_0$.

Discrete Time Characterization

We want to compare the robustness of the algorithms when implemented in discrete time; do they converge quickly?

We tune the parameters so that, when a single agent is used both PM and DA have similar performances

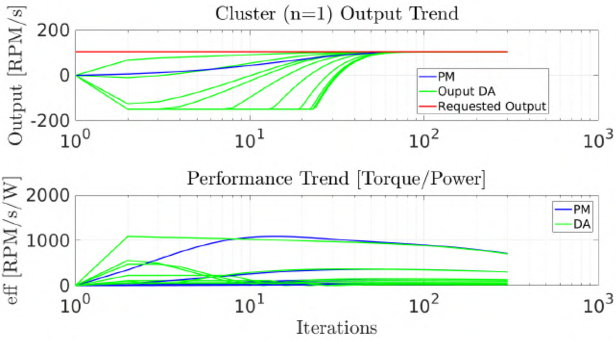
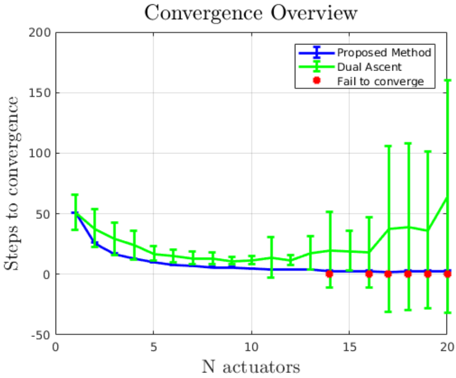


Figure: A set of tests with a single agent, starting from randomly selected initial conditions $\vec{\omega}_0$

Convergence for large clusters

For each number of agents, 100 tests are performed: 10 randomly chosen torque requests $\times$ 10 random starting condition $\vec{\omega}_0$ each.



Average number of iterations before convergence and standard deviation are displayed. Red dots mark failure to converge in at least one case.

Part II; Designing with clusters

Part I provides a method to control cluster effectively, both in terms of reliability, efficiency and with very mild theoretical requirements

Then, being able to coordinate large numbers of agents, we can either extend a cluster throughput

OR

we can use *smaller* components and combine them at will to better approximate the design optima

Moreover, with cluster we can obtain stronger theoretical assurances on the design optima itself

Part II structure:

1. Analytical results
2. Numerical validation of analytical results using an earth observation cubesat mission

Literature Review

Multidisciplinary Design Optimization methods implement a large constrained optimization in clever ways, but they all solve the same problem

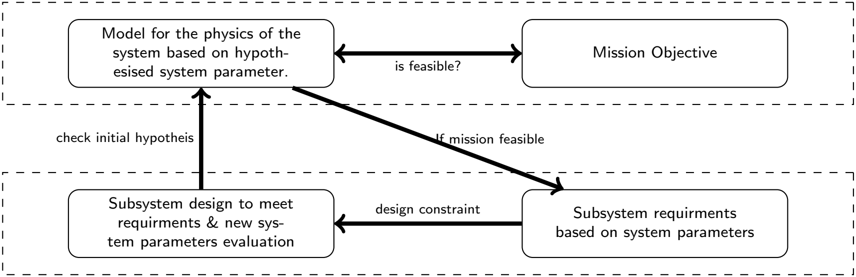
Choose how to represent a design point	$\Rightarrow$	Define the independent variables
Implement the physics that governs the problem	$\Rightarrow$	Define the constraints
Choose a criteria to decide which is the best design	$\Rightarrow$	Define a cost function and optimality condition

The optimization then **follows the gradient of the cost function** within the feasible region of the design space.

Design for clusters

Using clusters it is possible to use a **stronger** approach, more robust with respect to the cost function choice.

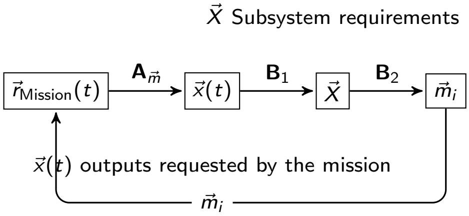
Main idea: system design can be model conceptually with the following scheme



By defining each step formally, we can study general proprieties like convergence, stability etc.

Existence and uniqueness of optima

We prove that, if the design cycle is a contraction map, there exists a unique design point which simultaneously minimizes a large class of cost functions.



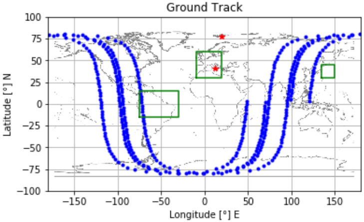
$\vec{m}_i$ = parameter derived from subsystem design

Software Implementation

High level

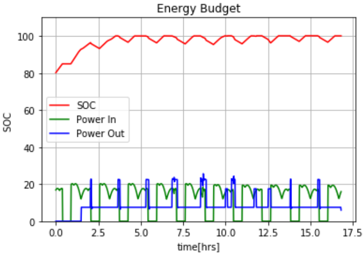
A Python framework has been developed:

- Given a **mission**
- Given a **satellite design**

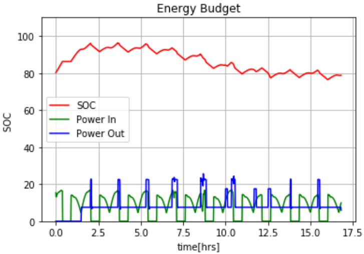


⇒ Simulates the mission and determines

FEASIBLE



NOT FEASIBLE



Feasibility Conditions

For a design to be *mission feasible*, each component must be able to pass its feasibility condition:

Component	Parameter	Test	Threshold	
RW	Authority	$\geq$	$\max_{t\in[0,t_{\text{end}}]} T(t)$	
Solar Array	$\int_0^t P_{\text{in}}(\tau)\,\mathrm{d}\tau$	$\geq$	$\int_0^t P_{\text{out}}(\tau)\mathrm{d}\tau$	$\forall t \in [0, t_{\text{end}}]$
Battery	20% of Capacity	$\geq$	$\max \Delta(\int_0^t P_{\text{in}}(\tau) - P_{\text{in}}(\tau)\mathrm{d}\tau)$	$\forall t \in [0, t_{\text{end}}]$

These conditions are required by the mathematical formulation and are a good approximation of intuitive requirements.

GOMX4B

We test the method on a real earth observation mission

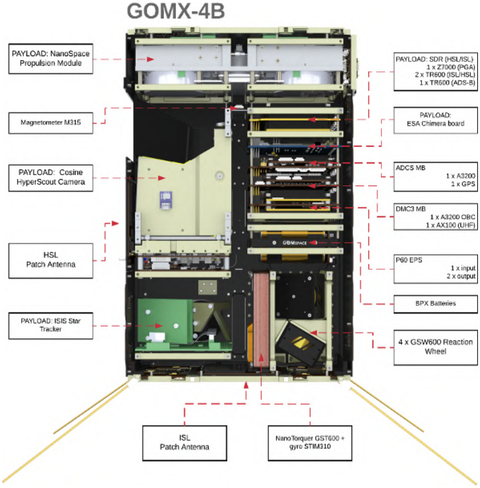
Orbit

- Sun Sync (LTAN 10 AM)
- $h = 500$ km
- Launch Feb 2018

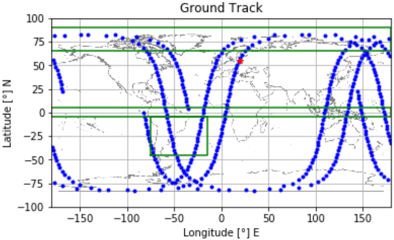
Desired behavior

Behavior as a function of *time*;

- Hyperscout to monitor Arctic
- Inter Satellite Link with GOMX 4A
- Chimera board to test memory
- Radio is ON above a GS



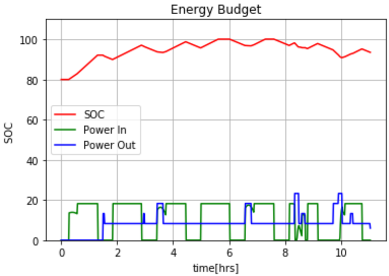
Operation Summary



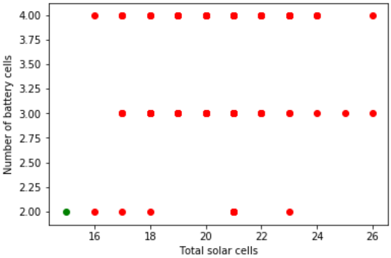
(a) Ground track and active zones

System	Figure	Value
[Eclipse]	avg duration	32.3 min
Radio	GS passes per day	5
Radio	length GS passes	7.3 min
Radio	duty cycle	2.5 %
HyperScout	operations per day	10
HyperScout	operations length	12.2 min
HyperScout	duty cycle	8.8 %
ISL	operations per day	2
ISL	operations length	7.9 min
ISL	duty cycle	1.3 %
Chimera	operations per day	7
Chimera	operations length	8.6 min
Chimera	duty cycle	4.2 %

Using monolithic battery pack

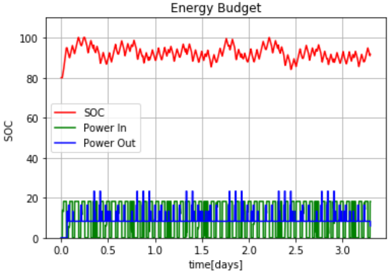


(a) Power trend on a short timescale, solution found by fixed point iteration

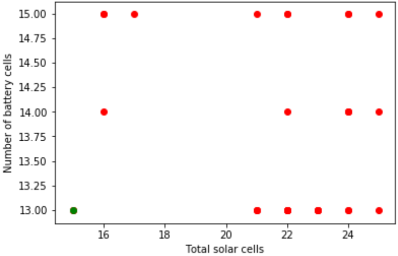


(b) Proposed Solution (green) VS other feasible solutions (1000 attempts)

Breaking up monolithic battery into its component cells



(a) Power trend on a short timescale, clusters of battery cells



(b) Proposed Solution (green) VS other feasible solutions (1000 attempts)

Figure	Cluster	Monolithic	Unit
Mean Solar Power	9.66	9.66	[W]
Mean Power Out	9.43	9.43	[W]
Max DOD	15.9	13.7	[%]
Satellite Mass	**7.90**	**8.05**	[kg]
Total solar cells	**15**	**15**	[#]
Battery capacity	**117**	**154**	[Whr]

Table: Result using clusters of batteries

Conclusions

1. The algorithm proposed can be used to increase system reliability and efficiency in both traditional clusters and virtual ones
2. Using cluster with large number of element we can either increase throughput or better approximate optimal design conditions
3. In specific cases, such as the design of small satellites, the use of clusters induce a unique optimum, thus providing a solution which is more robust to choices of cost function

Despite the technicalities of the proofs, both methods are *reasonably easy* to implement.

QUESTIONS?