Design and Testing of Clustered Components for Modular Spacecraft Architectures

Admission to third year

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(a) FSS Cat 5A

(b) FSS Cat 5B

Payloads:
1. Soil moisture and sea ice mapping
2. Optical Inter Satellite Link
3. RF federation experiment

1. Hyper-spectral earth imaging
2. Optical Inter Satellite Link
3. RF federation experiment
Immediate benefits of Redundancy

Cluster $\approx$ Redundancy $\Rightarrow$ Degrees of freedom for optimization.

Maximize Reliability

- Component failure is masked by redundancy.
- It assumes *independent* failures.
- *Required* for safety critical missions.

Maximize Performance

- Components are coordinated to maximize some function.
- Can reduce cost at fixed performance.

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**Figure:** Iperdrone; a 6U cubesat sponsored by ASI to assess the ISS

**Figure:** The Argo concept, based on redundant COTS start trackers.
Drivers that may lead to clusters

Modular designs:

- Design with basic independent units
- Reconfigurable and versatile
- The core function of each block will be redundant.

Simple Scaling properties:

- Hardware development is expensive
- Hardware testing is more expensive
- \( \Rightarrow \) Develop once, then copy-paste for scale.

(a) iBoss demo at IAC 2017

(b) Multiple Merlin engines in the FH
Reliability Vs Performance

Assuming the spacecraft has some redundancy, the classical architectures revolve around the ideas of parallelization or central control.

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Reliability</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Architecture Diagram" /></td>
<td>Good</td>
<td>As good as the individual component</td>
</tr>
<tr>
<td>Failure modes not independent, very hard to characterize (worst case: single point of failure)</td>
<td>Good</td>
<td></td>
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</tbody>
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Can we have both reliability and performance?
Overview

Assumption and nomenclature

- Assume Single Input - Single Output Agents
- No communication allowed
- All agent behave *nominally* in the same way
- The agent $i$ proposes a output $x_i$ and updates it according to a specific rule

Algorithm:

1. Starting from $x_i(t = t_j)$
2. Measure the global propriety $\Delta R$
3. Compute $x_i(t_j + dt)$ according to Eq. 1
4. Repeat from step 2

$$\frac{\partial x_i}{\partial t} = k \cdot \Delta R + \eta \cdot \frac{\partial C}{\partial x_i} \quad (1)$$
Visual Idea of behavior

Figure: Numerical simulation with two arbitrary actuators
Visual idea of Stability

Figure: Intuition for stability with two arbitrary actuators
Intuitive Explanation

\[ \frac{\partial x_i}{\partial t} = k \cdot \Delta R + \eta \cdot \frac{\partial C}{\partial x_i} \]

- \( \Delta R \) is a global property of the system
- \( C \) is a performance function, estimated internally by each agent
- \( k \) and \( \eta \) are positive constants that need to be tuned

Example:

- Starting condition \( x_1 = A, x_2 = B \)
- The system is not producing enough \( \Delta R = R - A - B > 0 \)
- Both agents increase production, but in different ways

![Graph showing the function C(x_i) with x_1 = A and x_2 = B]
Implementation details, measuring $C$

The curve Watt-Torque, $C$ depends on
- Engine constants ($k_v, k_c, R$ etc)
- Rotor angular velocity $\omega$

By measuring both power consumption and torque output, it is possible to update the estimates for the system constant using standard statistical tools.

![Diagram](image-url)

**Figure:** Electrical power required given $T$ and $\omega$
Benefits of insulation

Due to the constraints of independence, we have that
- The $C$ function is computed locally
- The $C$ is used, in real time, only locally

There is no need for these information to leave the subsystem.

- A lot of data can be gathered and processed locally, without added complexity for the system.
- Real time characterization of the agent performance, thus eliminating slow drift errors.
- Capability to autonomously adapt the behavior of agent to better suite environmental conditions.
- Real time monitoring the agents health and deterioration.
High level scheme for the individual agent

The temperature monitor on the engine will be used to validate the concept of statistically enriched regression model.
Conclusions

- Redundancy is pervasive in the space industry, either as a requirement or as a consequence of best practices.

- There exist at least one class of decentralized control algorithms able to maximize both reliability and a target performance function.

- A simple hardware demonstrator is under development to validate the implementation of the control schemes above.
List of Conference Papers and Presentations


Thanks for the attention!

Questions?
Broader Applications

In some cases, the benefit of redundancy might still not outweigh the costs of increasing system mass and volume.

Generalization:

- For some subsystem it is possible use the secondary effects of the actuators to perform an opportunistic thermal control.
- All subsystem produce heat.
- They could be coordinated to support an thermal control system.
- Using the framework of MIMO system, similar results can be achieved without explicit coordination.

![Diagram](image)  

\[ \Delta Q \]

\[ \sum q_i \]

**Figure:** Redundancy in the thermal control system due to inefficiencies