Distributed Actuation for Scalable Attitude Control of an On-Orbit Assembled Space Structure

David L. Bacher and John R. Cooper
Autonomous Integrated Systems Research Branch
NASA Langley Research Center
Hampton, Virginia 23666

***Abstract*—On-orbit assembly requires an attitude control scheme that can adapt to changing mass properties as the spacecraft is assembled. We propose a distributed attitude control scheme in which actuators such as reaction wheels and thrusters are spread throughout a modular space structure aboard a series of independent control modules. This work investigates methods for using the proposed distributed attitude control scheme to scale torque capacity in response to increasing inertia.**

I. Introduction

The vast majority of space systems have been assembled on the ground and launched aboard a single launch vehicle. Spacecraft designers contend with fundamental limitations on the mass, volume, and geometry of spacecraft imposed by available launch vehicles. Large structural elements are typically folded to fit inside a launch fairing and deployed in orbit. Autonomous on-orbit modular assembly would enable the deployment of large space structures over multiple launches. Unlike surface assembly, on-orbit assembly requires active attitude stabilization. Attitude Determination and Control Systems (ADCS) are designed taking into account the mass properties of the spacecraft, but these properties will change over the course of the assembly.

Performance of the ADCS is limited by the torque capacity of the onboard actuators. Many on-orbit assembly mission concepts such as those described in [4] and [1] involve building a structure on a spacecraft bus. An ADCS capable of managing the completed structure as well as any intermediate configurations would need to be present on the bus from the start, representing a significant up front cost in terms of development and mass to orbit. We propose modularizing and distributing the ADCS system across multiple independent spacecraft attached to the structure with their own onboard actuators. In this work, we investigate how torque capacity can be scaled by adding additional control modules.

II. Problem Formulation

In this work, we model the total spacecraft as a modular rigid body, as shown in Figure 1. We consider the 3DoF case in which the spacecraft rotates about its center of mass according to Euler's well-known equation of motion [3]:

$$\dot{\omega} = J_c^{-1}(\sum \tau_c - \omega \times J_c\omega) \tag{1}$$

where ω is the spacecraft's angular velocity vector, J_c is the spacecraft's inertia matrix about the center of mass, and

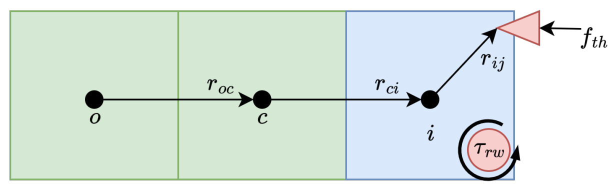

Fig. 1. Diagram of relevant vectors in the modular spacecraft model

$\sum \tau_c$ is the sum of external torques on the spacecraft about the center of mass, with contributions from the spacecraft's actuators and environmental disturbances.

In a particular intermediate assembly configuration, the spacecraft consists of n modules, each of which has a mass m_i. Because the center of mass changes over the course of the assembly, it is convenient to reference points of interest with respect to a point o fixed to the spacecraft geometry. The vector r_{oi} gives the position of the center of mass of module i with respect to o. The position of the center of mass of the entire spacecraft is given by:

$$r_{oc} = \frac{\sum m_i r_{oi}}{\sum m_i} \tag{2}$$

The inertia matrix of module i about its own center of mass is J_i. The position of each module's center of mass relative to the spacecraft's total center of mass is $r_{ci} = r_{oi} - r_{oc}$. The total inertia matrix of the spacecraft about the center of mass can be computed by the parallel axis theorem:

$$J_c = \sum_{i=1}^{n} [J_i + m_i({r_{ci}}^T r_{ci} I_3 - r_{ci}{r_{ci}}^T)] \tag{3}$$

The driving torque and angular velocity requirements vary from mission to mission. For the purposes of this investigation, we choose a representative requirement driven by a minimum-time slew maneuver in any axis. The minimum angular acceleration to complete a slew maneuver of angle θ_s about any axis in minimum time t_s defines a sphere in angular acceleration space, and multiplying by the inverse of the inertia matrix gives an ellipsoid in torque space:

$$\tau_{req} = J_c^{-1}\frac{2\theta_s}{{t_s}^2}\hat{n}_s \tag{4}$$

where $\hat{n}_s$ is the unit vector defining the axis of the slew maneuver.

At each stage of the assembly we need to choose $k \in \mathcal{N}$, where k is the next module to add to the structure. $\mathcal{N}$ is the subset of modules that are possible to add at the current decision step (for example, modules that would be floating in space would not be in $\mathcal{N}$). We also have a set β of modules to choose from. All modules will change J_c of the spacecraft, increasing τ_{req}. Active modules, which contain new actuators, also increase the torque envelope τ_{env}, which is the total amount of torque the spacecraft is capable of producing. We present a procedure for choosing the next k and β such that at every stage of the assembly, the spacecraft is capable of producing every torque inside the ellipsoid defined by (4).

III. Algorithm Description

We consider two common types of spacecraft actuators: reaction wheels and thrusters. Reaction wheels are mounted inside the spacecraft and produce a pure torque about the spacecraft's center of mass regardless of location. Thrusters are mounted on the surface of the spacecraft and produce both a linear force and a torque based on the moment arm between the force vector and the center of mass. The total torque τ_i produced by the actuators of module i is given by:

$$\tau_i = T_i u_i$$
$$T_{i,j} = \begin{cases} -\tau_{rw}, & \text{if } j \text{ is a reaction wheel} \\ (r_{ci} + r_{ij}) \times f_{th} & \text{if } j \text{ is a thruster} \end{cases} \tag{5}$$

r_{ci} is the position of module i with respect to c, and r_{ij} is the position of thruster j with respect to i. τ_{rw} and f_{th} are the maximum torque and force produced by the reaction wheel and thruster respectively. u_i is the normalized control vector for module i, where each element is restricted to be in $[-1, 1]$ for reaction wheels and $[0, 1]$ for thrusters. Equation (5) can be used to generate a convex hull in torque space representing τ_{env} [2]. If the ellipsoid τ_{req} is contained entirely within the convex hull τ_{env}, then the torque requirement is capable of being met. A torque margin can also be obtained by $\tau_{margin} = d_{min}(\tau_{env}, \tau_{req})$, the minimum distance between the surfaces of the torque envelope and the torque requirement ellipsoid, such that $\tau_{margin} > 0$ if τ_{req} is fully inside τ_{env}. The decision procedure is described in Algorithm (1).

Algorithm 1 New Module Decision Procedure

Initialize: Set of possible next modules $\mathcal{N}$
for $k \in \mathcal{N}$ and $\beta \in \{active, passive\}$ **do**
    Inertia matrix: $J_c \leftarrow (3)$
    Torque requirement: $\tau_{req} \leftarrow (4)$
    Torque envelope: $\tau_{env} \leftarrow (5)$
    Torque margin: $\tau_{margin} \leftarrow d_{min}(\tau_{env}, \tau_{req})$
end for
if $\tau_{margin} > 0$ for any passive modules **then**
    $k \leftarrow$ index of $\max \tau_{margin}[passive]$
    $\beta[k] \leftarrow passive$
else
    $k \leftarrow$ index of $\max \tau_{margin}[active]$
    $\beta[k] \leftarrow active$
end if

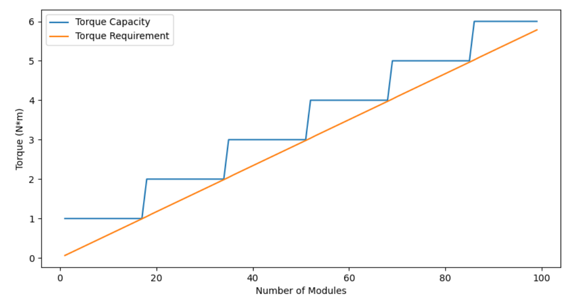

Fig. 2. Torque scaling under a lateral slew requirement

IV. Preliminary Results

To date, the above procedure has been applied to a one-dimensional rectangular beam consisting of cube-shaped modules. The active and inactive modules were chosen to have identical structural mass and dimensions, but the active modules had on-board reaction wheels allowing them to produce torque about all three principal axes of the spacecraft. Due to the extra mass of the reaction wheels, active modules had approximately 75% more total mass than the inactive modules.

In Figure 2, the required torque was computed based on a 30 second 90 degree slew. The decision algorithm placed active modules at regular intervals, successfully scaling torque capacity to meet the growing torque requirement about the lateral (least inertia) axis. However, it failed to keep up with the required torque capacity in all axes because the torque requirement scaled much faster than the torque capacity in the longitudinal (greatest inertia) axis, even when every single new module was active. Because every active module has the same set of reaction wheels on board, torque capacity cannot increase faster than linearly, but longitudinal inertia scaled cubically. Future work will investigate 2D and 3D structures where the algorithm can scale torque capacity in more than one axis.

References

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