Computationally-efficient modeling and optimization of strain-actuated solar arrays with tailored viscoelastic damping for spacecraft attitude control

Yong Hoon Lee[1], Vedant[2], and James T. Allison[3,2] | [1]Department of Mechanical Science and Engineering, [2]Department of Aerospace Engineering, [3]Department of Industrial and Enterprise Systems Engineering | University of Illinois at Urbana-Champaign

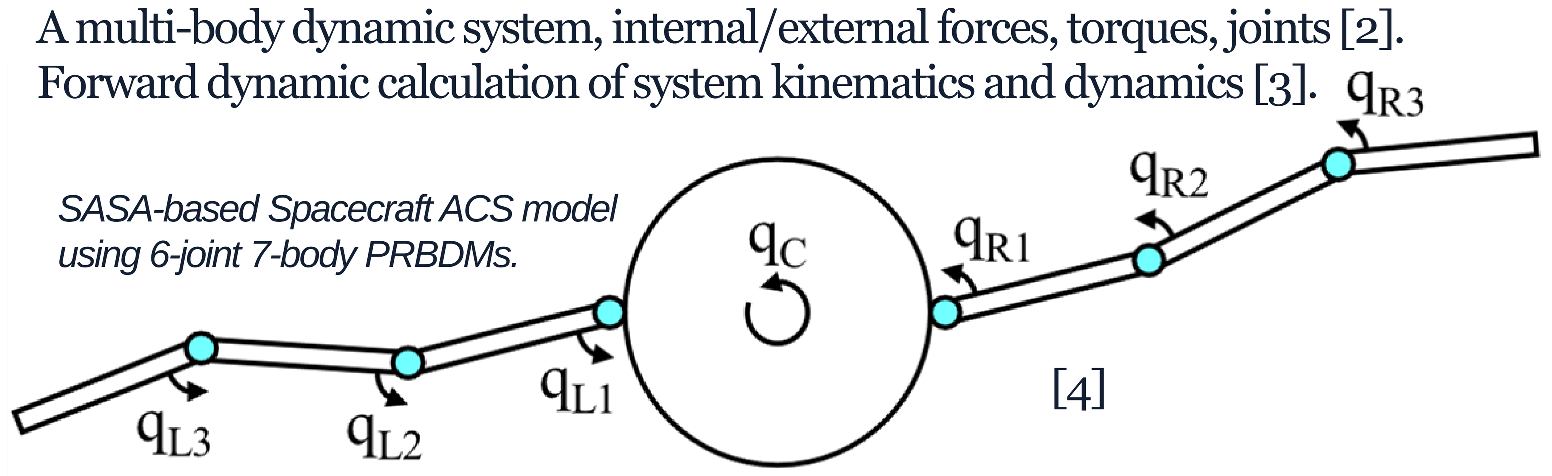
ABSTRACT

The recently-introduced strain-actuated solar array (SASA) spacecraft attitude control system (ACS) is expected to enable new levels of pointing precision for next-generation space observatories. Previous work has shown that tailored passive viscoelastic damping can help mitigate control system complexity by using passive damping to manage high-frequency vibration modes, while the active control system focuses on lower-frequency dynamics. Viscoelastic materials (VEMs) exhibit hysteretic behavior, requiring the use of computationally-expensive models based on integro-differential equations. A class of approximations is presented here where convolution integrals are replaced with linear time-invariant state-space equations with auxiliary states to reduce computational expense significantly, supporting the application of control co-design optimization, while maintaining requisite accuracy. This approach eliminates time history integration needed for derivative function calculation, which opens up the possibility of using general optimal control toolkits as well as advanced computationally-efficient methods for approximating system dynamics derivative functions.

SASA [1] BASED SPACECRAFT DYNAMICS MODELING

n-Revolute Joint Pseudo-Rigid-Body Dynamic Model (PRBDM)

- A multi-body dynamic system, internal/external forces, torques, joints [2].
- Forward dynamic calculation of system kinematics and dynamics [3].



- The dynamic equation of the PRBDM

$$M\left(\vec{\theta}(t),p\right)\ddot{\vec{\theta}}(t)+C\left(\vec{\theta}(t),\dot{\vec{\theta}}(t),p\right)\dot{\vec{\theta}}(t)+K(p)\vec{\theta}(t)=B(p)\vec{T}\left(t,\dot{\vec{\theta}}(t)\right)$$

where M: moment of inertia matrix, C: Coriolis force matrix, K: stiffness matrix, B: torque parameters, $\vec{T}$ is a torque vector, $\vec{T}=\vec{T}_c+\vec{T}_v$, p: plant parameters, $\vec{\theta}$: relative angular displacement vector, $\dot{\vec{\theta}}$: angular velocity vector.

Nested Control Co-Design Formulation

$$\begin{aligned} \min_{\vec{x}} \quad & \mathfrak{L}=\sum_i \int_{t_0}^{t_f} T_{c,i}(t)\,dt && \text{minimize E} \\ \text{subject to} \quad & \dot{\vec{\xi}}_s(t)-\vec{f}_{d,s}\left(t,\vec{\xi}_s(t),\vec{T}_c(t),\vec{T}_v\left(\vec{\xi}_v(t)\right)\right)=\vec{0} && \text{dynamics} \\ & \dot{\vec{\xi}}_v(t)-\vec{f}_{d,v}\left(t,\vec{\xi}_v(t),\vec{\xi}_s(t)\right)=\vec{0} && \text{VE damping} \\ & \vec{C}\left(t,\vec{\xi}(t),\vec{T}_c(t),t_0,\vec{\xi}(t_0)\right)\leq\vec{0} && \text{constraints} \end{aligned}$$

- Material function design for viscoelastic damping is relatively expensive [4].
- Control design using direct transcription is computationally-efficient but requires a massive number of function evaluations.
- Outer-loop: stress relaxation kernel function design for VED using GA,
- Inner-loop: control design using a Legendre pseudospectral method and NLP.

Multi-Interval Legendre Pseudospectral Direct Optimal Control Method

- Lagrange polynomial and Legendre-Gauss-Lobatto (LGL) collocation points [5].

STATE-SPACE APPROXIMATION OF CONVOLUTION INTEGRAL

Modeling Viscoelastic Damping: $T_{v,i}(t)=-\int_{-\infty}^{t} G(t-\tau)\dot{\theta}_i(\tau)\,d\tau$ [6]

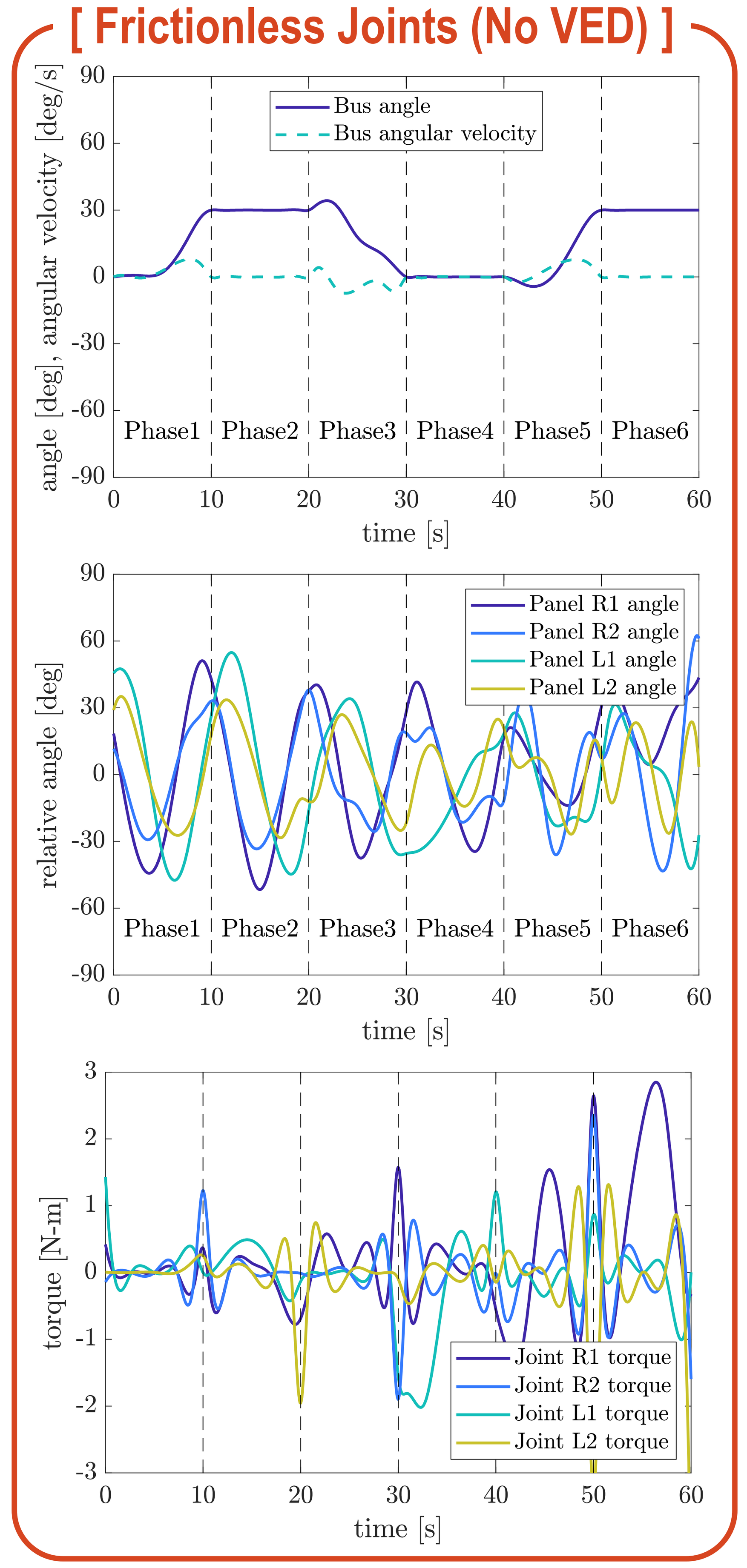
- Stress relaxation kernel $G(t)$
  - Monotonically-decreasing function,
  - Can be parameterized with existing material models, e.g., multi-mode Maxwell model
- Convolution integral enumerates the entire time horizon at every time step: too expensive.
- State-space approximation converts the convolution integral to an LTI equation, which has a Markovian characteristic (future behavior is only dependent on the current state).

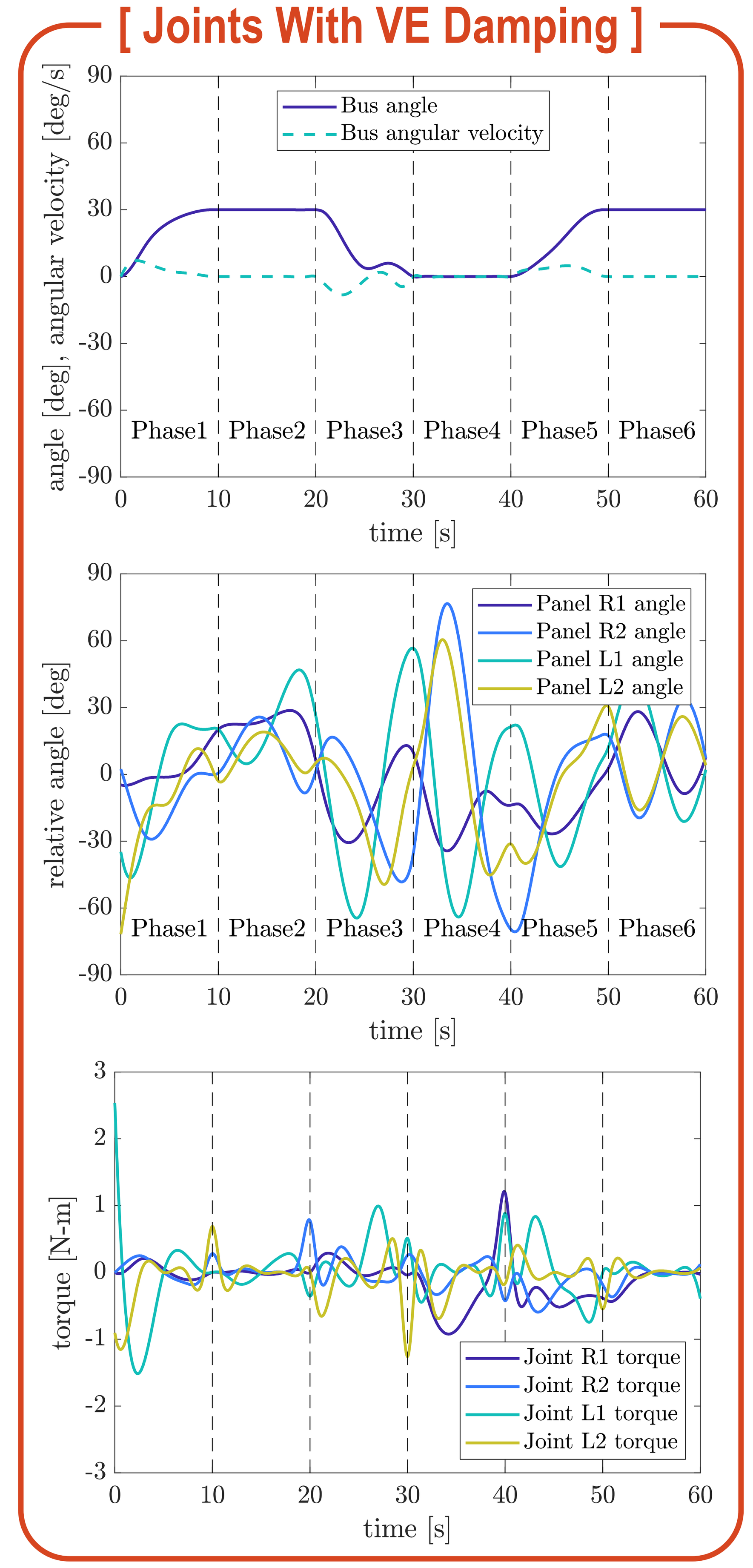
State-Space Approximation with Prony Basis Function

- An LTISS [5,7]: $\tilde{T}_{v,i}(t)=-\int_{-\infty}^{t}\tilde{G}(t-\tau)\dot{\theta}_i(\tau)\,d\tau=\begin{cases}\dot{\xi}_v(t)=A_v\xi_v(t)+B_v\dot{\theta}_i(t)\\ \tilde{T}_{v,i}(t)=C_v\xi_v(t)\end{cases}$
- A single Prony basis function [8]: $\phi(t)=C_{v,\phi}e^{A_{v,\phi}t}B_{v,\phi}$

where $A_{v,\phi}=\begin{bmatrix}-\theta_2 & \theta_3\\ -\theta_3 & -\theta_2\end{bmatrix}$, $B_{v,\phi}=\theta_1\begin{bmatrix}\sin(\theta_4)\\ \cos(\theta_4)\end{bmatrix}$, $C_{v,\phi}=\begin{bmatrix}0\\ 1\end{bmatrix}^{\mathrm{T}}$

RESULTS





FINDINGS AND CONCLUSIONS

We formulated a strain-actuated solar array (SASA) based spacecraft ACS system model with a computationally-efficient viscoelastic damping model using the state-space approximation technique. Co-designing tailored viscoelastic damping along with the SASA-based spacecraft ACS mitigated panel vibration, resulting in less panel movement for maintaining target pose trajectories.

Our findings include:

- Spacecraft bus angular trajectory become smoother with added damping.
- Although larger control angles were required for joints with VED, stationary states for the spacecraft bus (Phase 2, 4, and 6) mostly required less panel movement to maintain the stationary pose.
- Overall energy consumption for the SASA with VEM is significantly less than the frictionless case, although control torque needed to overcome damping forces.

Future work:

- Numerically implement distributed continuous damping, instead of joint damping.
- Investigate possibilities of real-time open-loop control using the VED.
- Numerically implement Multifunctional Structure for Attitude Control (MSAC).

Please refer to the paper presented on Sat. February 1, 2020 (Vedant et al., AAS 20-018) to get more information about the MSAC, a novel ACS method recently developed.

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