National Aeronautics and Space Administration

Transient Instabilities in Swarm Formations, Deployable Structures, and In-Space Assembled Structures and the Development of Mitigation Strategies

Principal Investigator: Saptarshi Bandyopadhyay (347); Co-Investigators: David Bayard (343), Samuel Bradford (355), Marco Quadrelli (347), Mark Balas (Texas A&M University)

Program: FY21 R&TD Topics **Strategic Focus Area: Swarms**

The objective of this project is to lay the foundations of powerful control-theoretic methodologies to detect and mitigate transient instabilities in swarms and deployable structures.

Transient instability in swarms is defined as the phenomenon of increasing-amplitude oscillations within the swarm that leads to inter-agent collisions, in spite of the swarm being asymptotically-stable in its steady-state. We developed a mathematical framework “theoretical tool” to detect transient instability.

Simultaneous guarantees for dynamic stability, in the Lyapunov sense, and collision mitigation in autonomous formations are challenging to obtain. A Transient Trajectory Controller (TTC) incorporates a novel projection operator-based collision-free trajectory generator, and tracking controller, that modifies the transient dynamics to prevent collisions between agents. This architecture can simultaneously guarantee dynamic stability and transient stability in swarms. The TTC architecture is also robust to bounded persistent, and unmodelled disturbances.

In Year 2, we focused on the dynamical behavior of deployable booms and the important challenge of avoiding collisions between boom's structural elements or with other parts of the spacecraft, that can potentially have serious consequences. We define this kind of collisions as “transient instabilities” in deployable booms. A new paradigm to tackle these issues was developed, using techniques from multi-agent/swarm literature like transient instability prevention methods that avoid inter-agent collisions. We have adapted these techniques to deployable booms to guarantee safe deployment of booms and avoid collisions. We also present computational simulations of boom deployment in order to validate our techniques and demonstrate its use for future space missions.

An initial unstable deployment is simulated, switching off the control function, resulting in inter-segment and segment- spacecraft collisions, with a constraint ratio function constantly exceeding the limit value of 1 for transient stability, as observed in Fig. 4.

By contrast, if the control function is switched on, a fully stable deployment takes place as it can be observed in Fig. 5. Specifically, it can be seen how the constraint ratio function always remains below the limit value of 1, thus fulfilling the theoretical framework provided within this work, as well as the stiffness and damping values of each of the hinges are varied automatically over the simulation period to achieve the transient stability property of the mechanical structure.

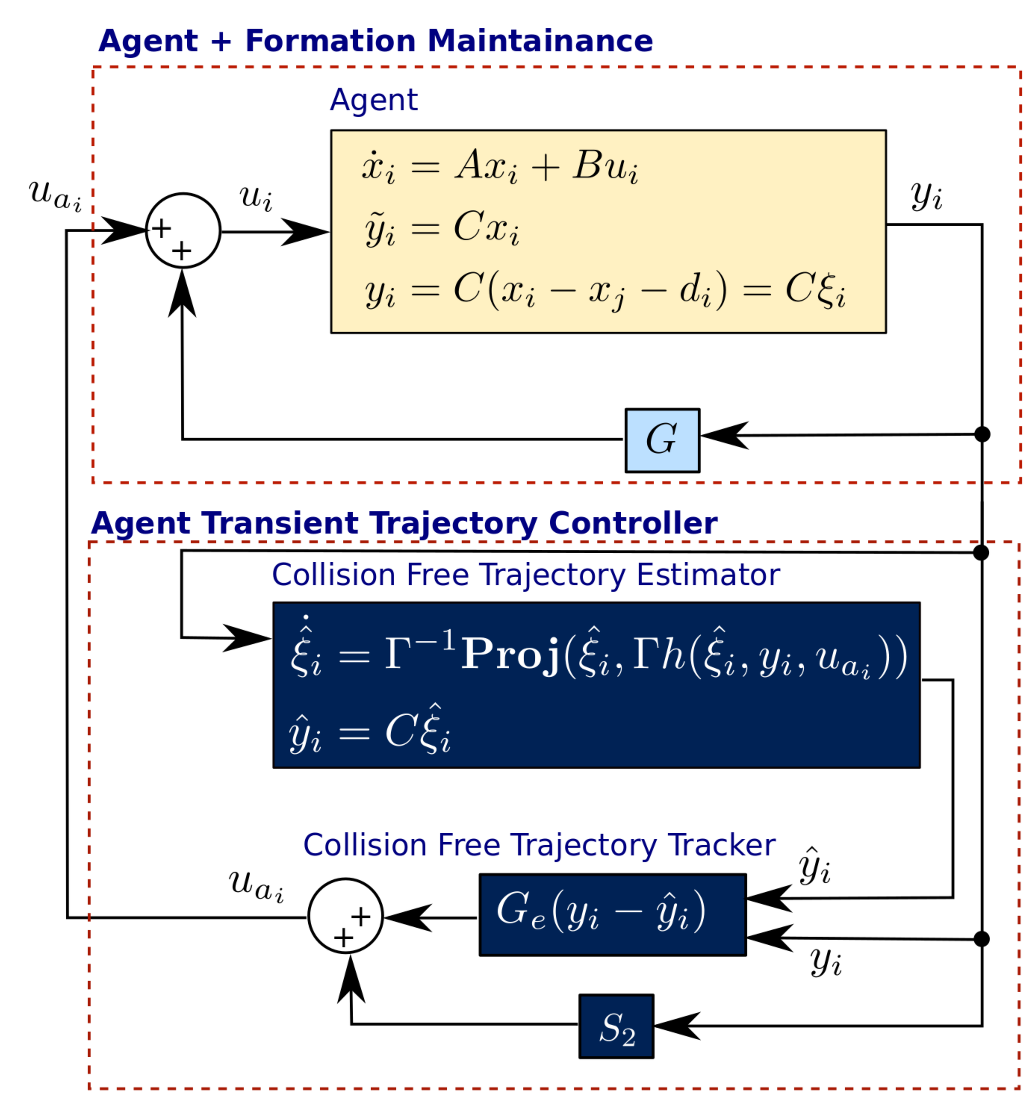

Figure 1. Dynamic Stability and Collision Mitigation Control Architecture, called Transient Trajectory Controller (TTC)

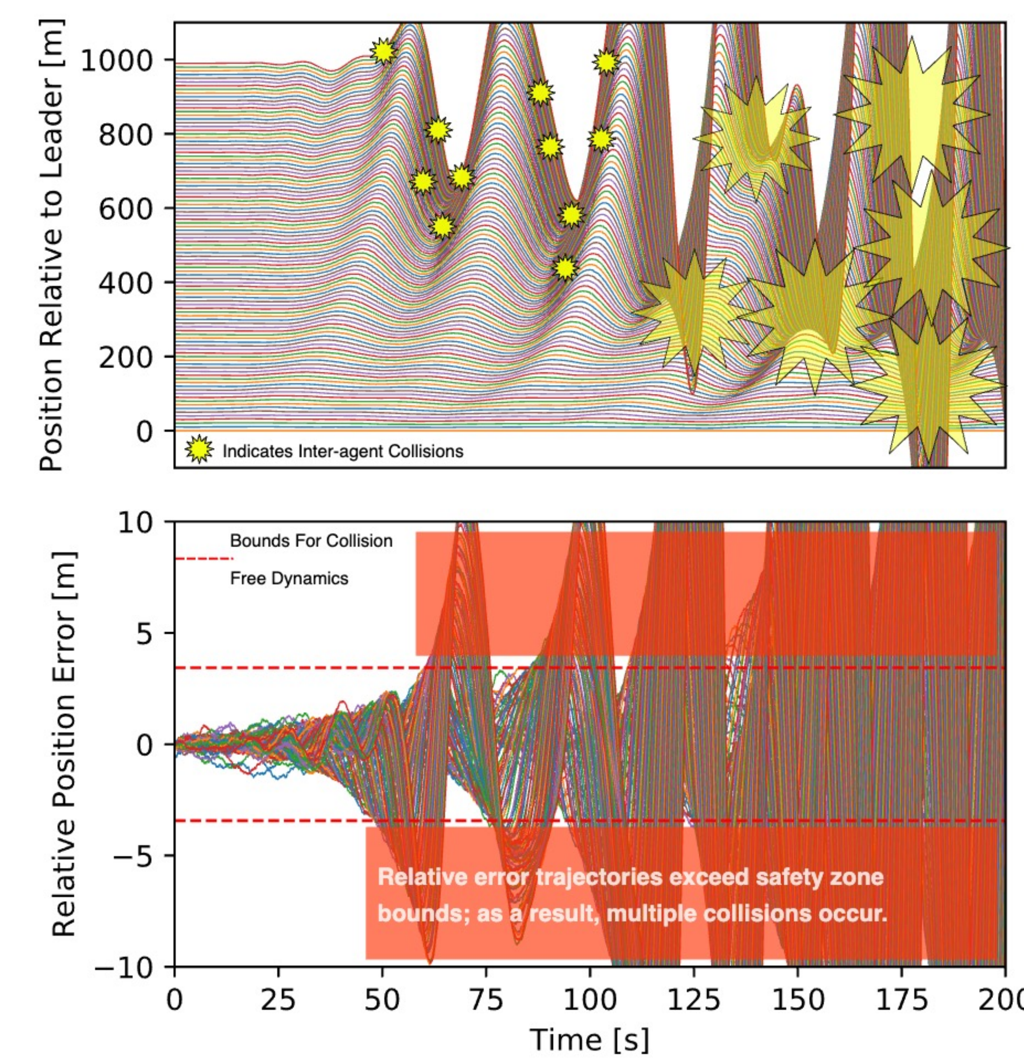

Figure 2. 100 Agent Serial-Chain with TTC disabled, which leads to inter-agent collisions

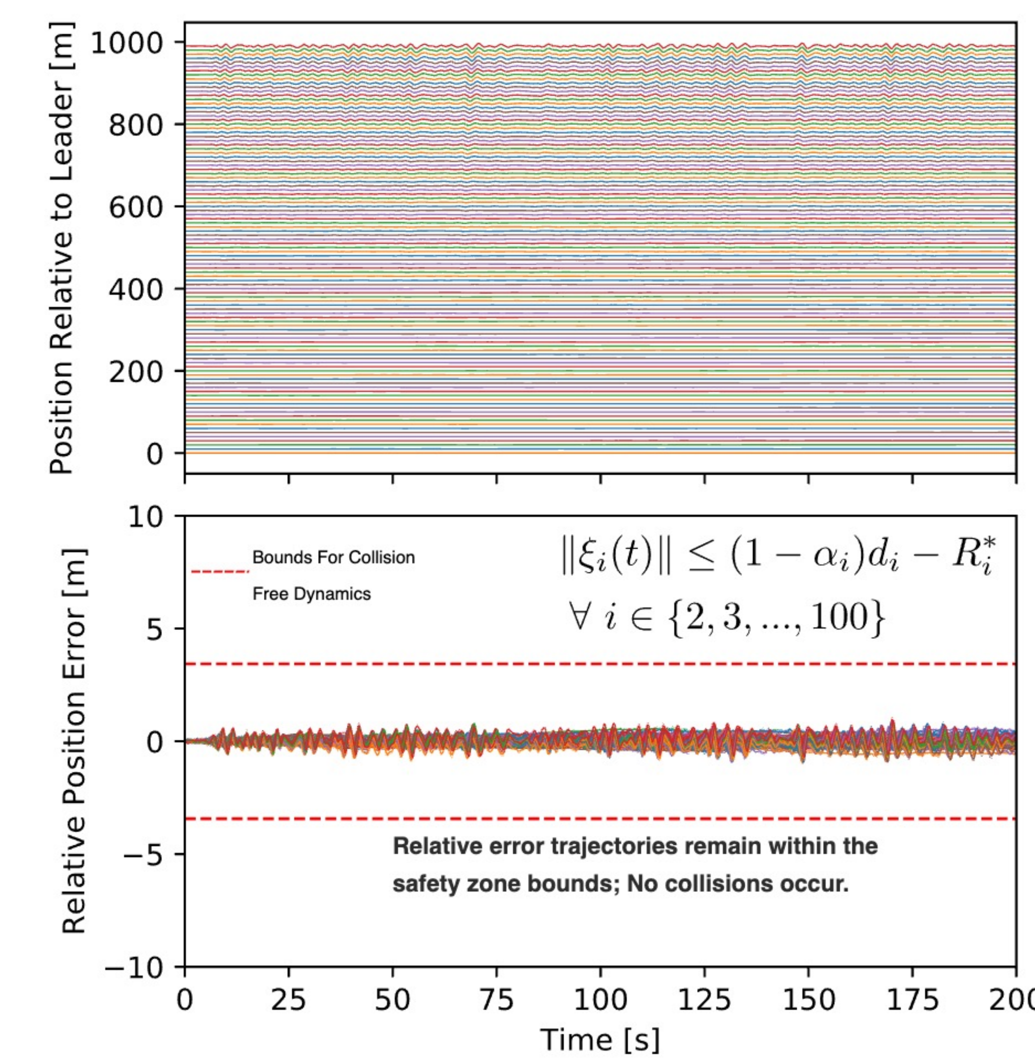

Figure 3. 100 Agent Serial-Chain with TTC and “Ripple-Communication” Enabled

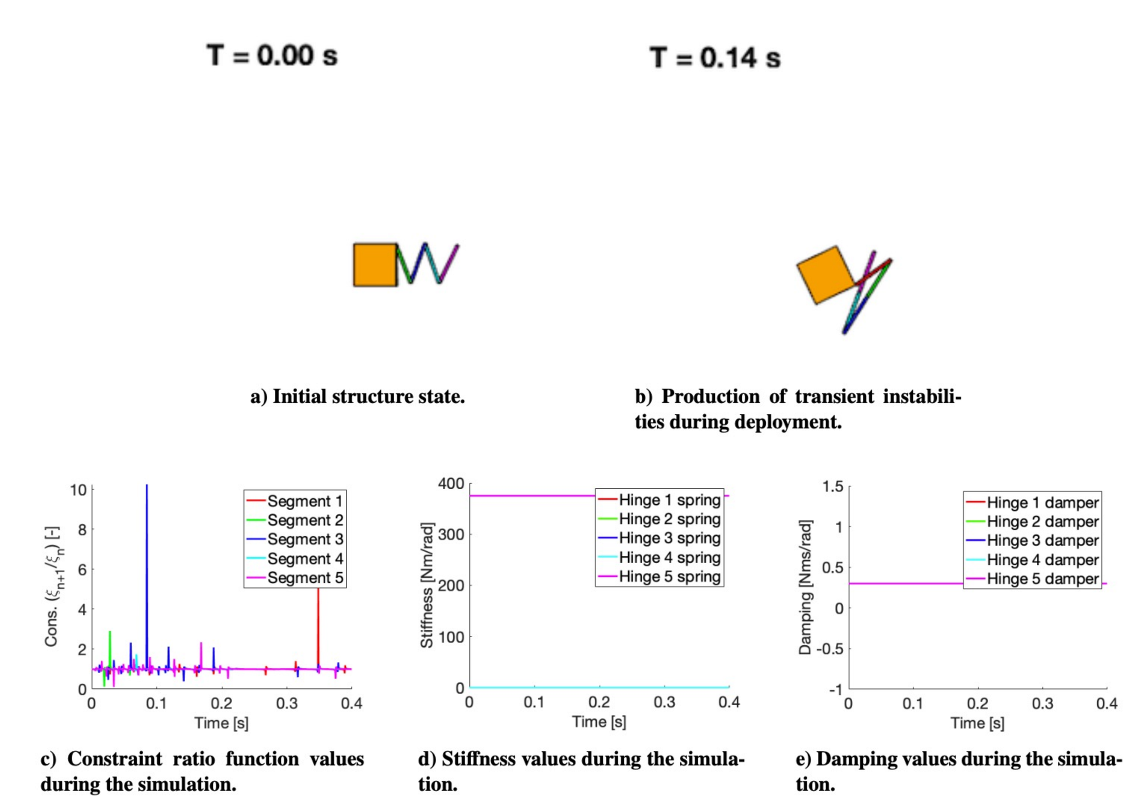

Figure 4. Non-controlled structure deployment

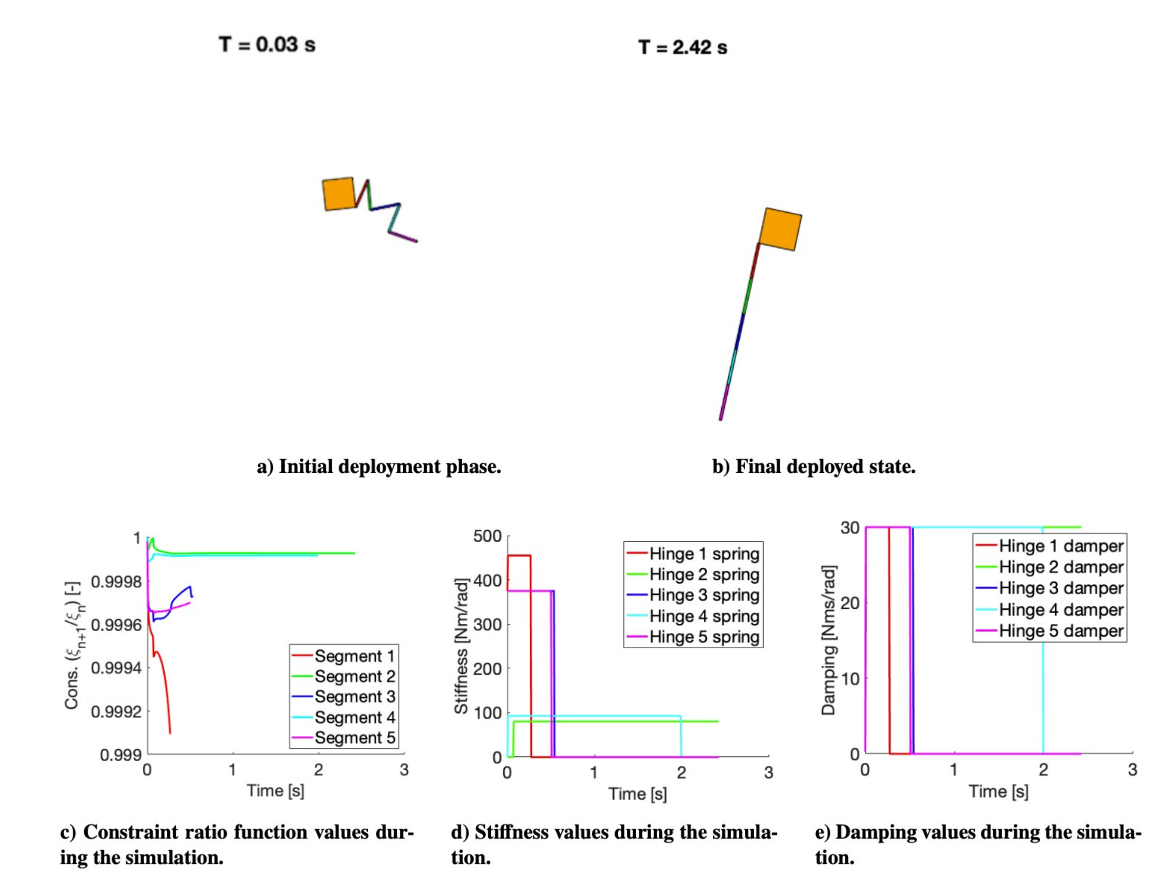

Figure 5. Actively controlled structure deployment

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

ACKNOWLEDGEMENTS
We would like to thank Dr. Vinod Gehlot from TAMU and JVSRP intern Juan L. de Pablos from IMDEA Materials Institute, Spain for their contributions to this project.

PUBLICATIONS
[A] V. Gehlot, S. Bandyopadhyay, M. Balas, D. Bayard, M. Quadrelli, “Detection and Mitigation of Transient Instabilities in Multi-Agent Systems and Swarms”, IEEE Transactions on Control of Networked Systems, 2021. under preparation.
[B] J. L. de Pablos, S. Bandyopadhyay, M. Quadrelli, D. Bayard, S. C. Bradford, V. Gehlot, M. Balas, “Detection and Mitigation of Transient Instabilities in Deployable Booms”, AIAA SciTech Spacecraft Structures, January 2022, accepted.
[C] V. Gehlot, M. Balas, S. Bandyopadhyay, M. Quadrelli, D. Bayard, S. C. Bradford, J. L. de Pablos, “Multi-Agent Control Approach to the Stability of Linear Deployable Systems”, AIAA SciTech Guidance, Navigation, and Control (GNC), January 2022, accepted.
[D] S. Bandyopadhyay, V. Gehlot, M. Balas, M. Quadrelli, D. Bayard, “Detection of Transient Instabilities in Swarms”, IEEE American Control Conference (ACC), New Orleans, LA, May 2021.
[E] V. Gehlot, M. Balas, S. Bandyopadhyay, M. Quadrelli, D. Bayard, “Mitigation of Transient Instability in Formations of Dynamics Agents Using Projection Based Estimators”, IEEE American Control Conference (ACC), New Orleans, LA, May 2021.
[F] S. Bandyopadhyay, V. Gehlot, M. Quadrelli, D. Bayard, M. Balas, “Detection and Mitigation of Transient Instabilities in Multi-Agent Systems and Swarms”, International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Oct. 2020.
[G] V. Gehlot, M. Balas, S. Bandyopadhyay, M. Quadrelli, D. Bayard, “Projection-Based Inter-Agent Collision Avoidance in Dual Agent Systems”, International Conference on Autonomic and Autonomous Systems (ICAS), Lisbon, Portugal, Sept. 2020.
[H] V. Gehlot, M. Balas, and S. Bandyopadhyay, “Dynamic Stability And Adaptive Control of Networked Evolving Formations with Weak Nonlinearities”, AIAA Guidance Navigation and Control (GNC) Conference, Orlando, FL, Jan. 2020.

PI/Task Mgr Contact
Email: Saptarshi.Bandyopadhyay@jpl.nasa.gov

Clearance Number:
RPC/JPL Task Number: R20131