MPP: Final Report

Autonomous Robotic Assembly of Space Structures using On-Orbit Additive Manufacturing for Near-Earth Observation and Space Environment Missions

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Professor Richard Linares
Charles Stark Draper Assistant Professor
Co-Director Space Systems Lab
MIT

Professor Rodrigo Ventura
Assistant Professor of Electrical and Computer Engineering
Instituto Superior Técnico, University of Lisbon

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I. Project Summary and Algorithm Overview:

The "**Autonomous Robotic Assembly of Space Structures using On-Orbit Additive Manufacturing for Near-Earth Observation and Space Environment Missions"** project, also known as the Astrobee-ReSWARM project (MPP/ReSWARM), builds on the prior work of SPHERES-ReSWARM, a decentralized control and planning testing campaign demonstrating advanced graph- and MPC-based control algorithms for future microgravity cooperative satellite teams. Further, Astrobee-ReSWARM begins to consider another important problem for on-orbit servicing, repair, and assembly called the information-aware planning problem. New space-borne observatories and large orbital outposts can be enabled by robotic assembly of space structures using techniques like on-orbit additive manufacturing which can provide flexibility in constructing and even repairing complex hardware. However, future autonomous microgravity systems will likely encounter frequent changes in their dynamics parameters as they manipulate objects, reposition space structures, and aggregate with one another. Being able to simultaneously perform motion planning while encouraging parameter learning to understand system changes will be valuable and complementary to swarm-based tasks.

The objective of the previous SPHERES-ReSWARM project was to test maintaining and steering formation configurations using the SPHERES free-flyers onboard the International Space Station (ISS). This configuration would be maintained by scalable, fast control of individual vehicles within the swarm (formation control), and steered by centralized control toward a specific goal (governance control). Additionally, a model predictive control (MPC) scheme that would prepare the formation to face unpredictable events such as thruster failure would be tested. Two SPHERES test sessions were planned---the first to test the basic algorithm consisting of formation and governance control as well as their integrated performance, and the second to build upon the limitations found in the first and introduce uncertainties and failures.

ReSWARM's original statement of work included the operation of these two ISS test sessions on the SPHERES platform. The first session was run successfully, but due to unforeseeable setbacks on station, the second test session was not completed fully. Following the first test session, MIT and NASA jointly troubleshooted to resolve the problem, resulting in a second instance of ReSWARM session #2 (Dec 31, 2019) This was also the final test session for SPHERES. Knowing that battery time was very limited, the team was able to start the main tests three times and complete approximately one minute out of six minutes from each of the runs; however, this was not enough time to run the desired NMPC and collect useful data. Following battery depletion, the remainder of the allocated session time was used by the Ames team to continue the commissioning of Astrobee.

Astrobee-ReSWARM allows for the science goals of the original second ISS test session to take place using the Astrobee testbed in lieu of the original SPHERES facilities, which were retired in December 2019. Astrobee has the ability to perform the test objectives of demonstrating robustness to uncertainty and system failures and would be a capable platform for the project's continuation. In addition, the project has expanded to include a set of algorithms used for simultaneously characterizing unknown system dynamics parameters (like moments of inertia) while achieving useful motion. The swarming and information-aware algorithms complement one another, as cooperative multi-agent on-orbit robots will frequently encounter situations where uncertainty characterization is a key consideration while motion planning.

The ReSWARM project's swarm control portion defines control algorithms that distinguish the task of maintaining a formation geometry and the one of steering it across the environment, relaxing communication requirements within the formation. The formation geometry is maintained using relative sensing and minimum/no communication in order to provide a scalable, stable and fast control of the satellites with less dependence on the knowledge of the absolute states of the satellites. The proposed formation control approach is divided into two parts. Firstly, the formation geometry is maintained using relative sensing capabilities and minimum/no inter-satellite communication, without a need for the satellites to know their absolute positions in the environment. Secondly, the formation is navigated in the environment using the knowledge of the center of the formation and moving it to the desired goal. This project explores two methods of the previous approach. The first method, denoted graph-based control method, is more reactive and with less computational complexity that scales well with the number of satellites in the system. A second method, denoted the model predictive control method, uses a more advanced controller based on a Model Predictive Control scheme to adapt formation planning to model uncertainties (e.g., to satellite thruster failures), taking into account the relative position errors between all the satellites. The project is divided into two steps. In a first step, the basic implementation and feasibility testing of the ReSWARM algorithms are performed, using a first test session (experiments reported in this document). A second step will consist of the comparison of the two suggested methods for formation control, with a second test session. Successful control of a two-Astrobee "swarm" in a low-risk six degree of freedom (DOF) microgravity environment aboard ISS will mature the ReSWARM algorithms for future use in similar but higher-risk impulsive propulsion space platforms.

The second objective is to address both the motion planning and control for robotic assembly with consideration of the inertial estimation with an object-manipulating Astrobee system. Specifically, dynamically feasible paths are obtained that are collision-free to a desired target to mimic the on-orbit assembly process. Model learning is incorporated explicitly into the planning stages via an online parameter estimation and information-aware planning framework. Remaining uncertainty can then be dealt with explicitly via robust model predictive control techniques. For inertial estimation, the information-aware planning framework utilizes a multi-tiered planning algorithm with high-, mid-, and low-level planning components representing increasing levels of model fidelity. At the mid-level planning layer, trajectory optimization using information metrics (e.g., the Fisher Information), is able to produce informative motion to promote learning of unknown system parameters, in combination with a an online parameter estimation scheme (parameter EKF), another beneficial algorithm for future autonomous microgravity satellite systems. By tracking robustly controlled trajectories that consider both obstacle avoidance and learning of the inertial properties online, future free-flyers will be able to execute complex collision-free trajectory planning with enhanced controller guarantees on safety. The approach naturally generalizes to repairing, refueling, and re-provisioning space structure components while providing optimal collision-free trajectories under e.g., inertial uncertainty. These technologies have been incorporated into the Astrobee-ReSWARM test sessions, conducted jointly with partners at University of Lisbon, IST.

II. Project Milestones and Schedule:

The updated project milestones (green) are provided in the Gantt chart in Figure 1. At this time, ReSWARM-2 on-orbit testing is complete; data analysis is in progress (ReSWARM-2 data received on Dec-10, 2021) and the team is awaiting imagery from ReSWARM-2. Two test sessions on the International Space Station were conducted demonstrating the aforementioned algorithms. All milestones related to on-orbit testing are complete for MPP/ReSWARM.

Milestones (2020-2021, months)	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Support														
Progress Report 1														
Progress Report 2														
Post-Test Report														
Final Summary Report														
Swarm MPC algorithm														
Algorithm verified: standalone C++/Python code														
Demonstration in Astrobee simulation: ROS integration														
Information-aware planning framework														
Low-level planner (MPC)														

Figure 1: Gantt chart of major algorithmic and integration tasks for ground and ISS software readiness to run on the Astrobee free-flyers. Original schedule is shown in blue; updated

schedule is shown in green. Tasks are highlighted with red for not started, yellow for in progress, green for complete/complete except for small changes.

III. Preflight Activities Completed to Date and Summary of Progress:

- Creation of a Flight Software guide for integration with Astrobee's Flight software [1]. Guide is now provided by NASA Ames on the default Astrobee repository.
- Initial ground testing of the first model predictive controller on Astrobee ground hardware.
- Integration of the information-aware planning framework with the Astrobee Flight Software, including parameter estimation.
- Initial integration of the swarm MPC algorithm.
- Summary of progress and reporting to the community at the iSAIRAS conference and Astrobee Working Group meeting [2][3][4][9].
- Reporting Astrobee and algorithmic in motion planning and control to the community [5][6][7][8].
- Submission of the Crew Procedures.
- S/G Enablement training for ReSWARM Operations.
- Adaptation of ROAM commanding, telemetry, and comms infrastructure for ReSWARM use; validated during ground testing.
- Completion of cross-compilation and hardware integration of software.
- Completion of >10 Astrobee ground test days and two orbital readiness test at NASA Ames for the ReSWARM on-orbit sessions.
- On-time software delivery for both ReSWARM sessions.

MPP/ReSWARM has successfully completed both of its test sessions on the ISS, on **August 19th** and **December 4th**, 2021. The ReSWARM-1 tests contained four components including: (I) general checkout of the algorithms (1 test), (II) distributed model predictive control with two Astrobees (3 tests), (III) on-orbit assembly motion planning and control (5 tests), and (IV) on-orbit assembly under inertial uncertainty (6 tests). Since the first ground demonstration on **July 9th**, the team tested these components in detail over 3 ground tests between **July 15th to July 29th**, and an Orbital Readiness Test on **July 23rd**. A safety memo was submitted for approval on **May 20th**, 2021, and approved for both sessions. Hardware integration, cross-compilation, and test commanding have been completed using ROAM infrastructure created by MIT. For operations during ReSWARM-1 individual members of MPP/ReSWARM took S/G enablement training required for communications. The ISS operations setup developed at MIT for earlier investigations was used for MPP/ReSWARM flight ops.

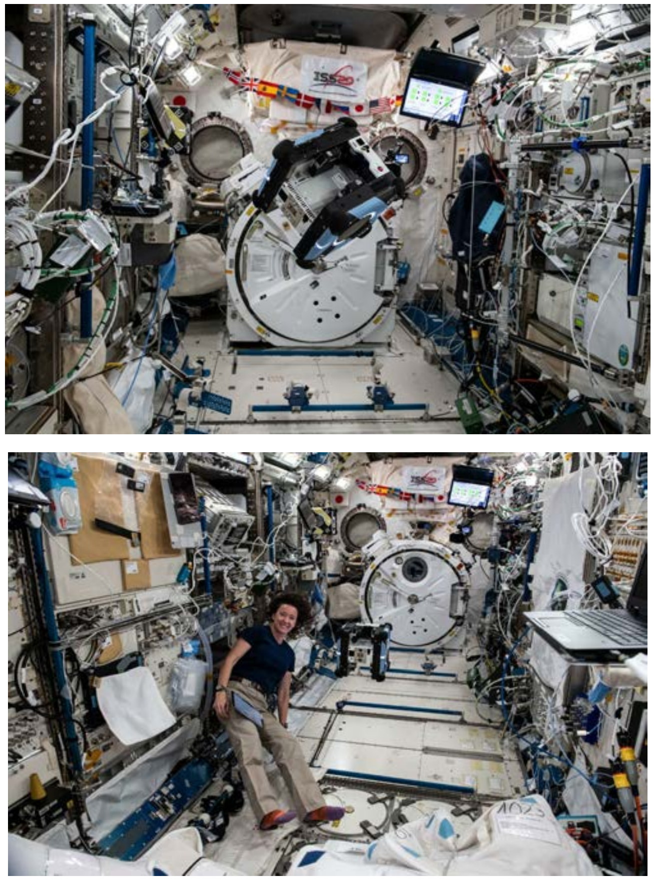

Figure: Astrobee executes a motion plan (top) and regulates next to crew member Megan McArthur (bottom).

One of the two Astrobees, Honey, failed to boot prior to testing, and the multi-robot tests (II) could not be performed. Additional runs of tests (III) and (IV) were conducted and the collected experimental data was used to further improve the algorithms in post-processing. The portion of software corresponding to test (IV), on-orbit assembly under uncertainty, underwent the most development, with the addition and integration of a total of four planning and estimation components. The motion planning under parametric uncertainty approach, RATTLE, was also upgraded to include online updates of unknown parameters, among other changes. After rigorous testing on the Astrobee Robot Software simulator, the code was readied for the next round of ground testing and ReSWARM-2 ops. New tests were introduced corresponding to the updated algorithmic development, with a breakdown of: (I) general checkout of the algorithms (1 test), (II) distributed model predictive control with two Astrobees (3 tests), (III) on-orbit assembly motion planning and control (2 tests), (IV) on-orbit assembly under inertial uncertainty (9 tests), and (V) complete on-orbit assembly pipeline combining frameworks from (III) and (IV) (1 test). 6 ground tests were conducted between **October 6th to November 11th, 2021**, before ReSWARM-2 ops on December 4th. ReSWARM-2 ops were successful, with a total of 39 successful test runs (an informal Astrobee record), with all primary test objectives met.

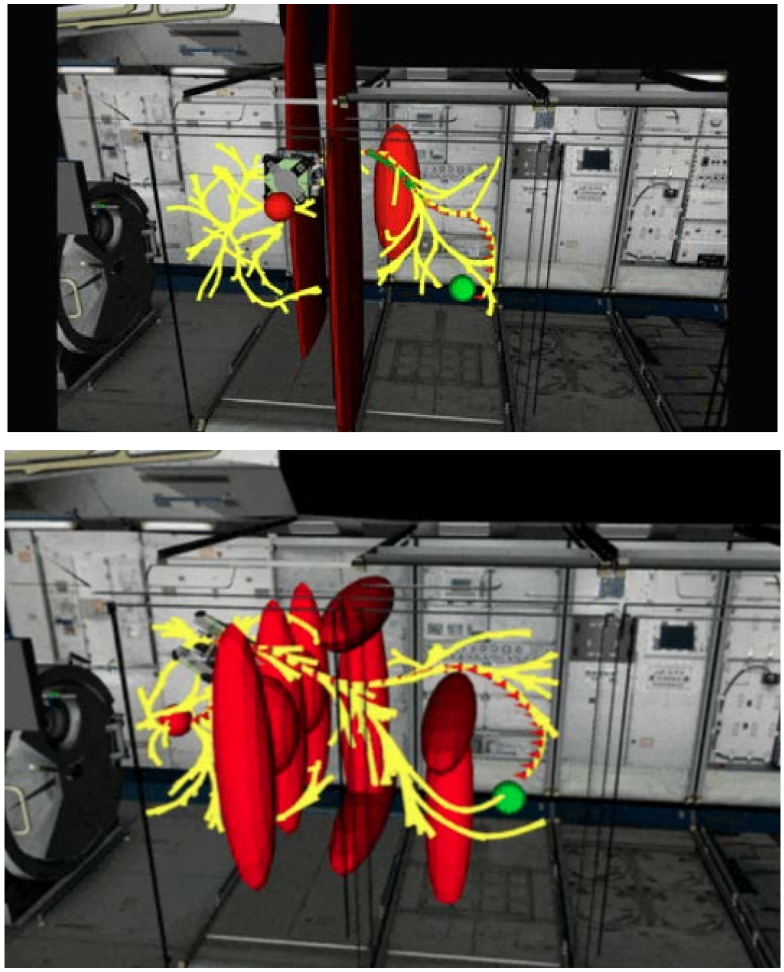

Figure: An example of the information aware motion planning algorithm running in simulation (red line: global plan; green line: local plan; red ellipses; obstacles) for an “astronaut” obstacle replan (top) and the “MIT” obstacle set (bottom).

Data analysis is now underway for both ReSWARM-1 and ReSWARM-2. Preliminary and simulation results are shown, highlighting the RATTLE motion planner, trajectory smoothing, and on-orbit robust control. In particular, some highlights of the results so far are the effectiveness of robust control for cautious/safe trajectory tracking, and fast real-time trajectory computation and replaning onboard the Astrobee robots. DMPC data from ReSWARM-2 is still in the early stages of analysis.

ReSWARM-2 data was downlinked on **December 10**, and is currently undergoing analysis; results for both sessions will be summarized in multiple forthcoming papers.

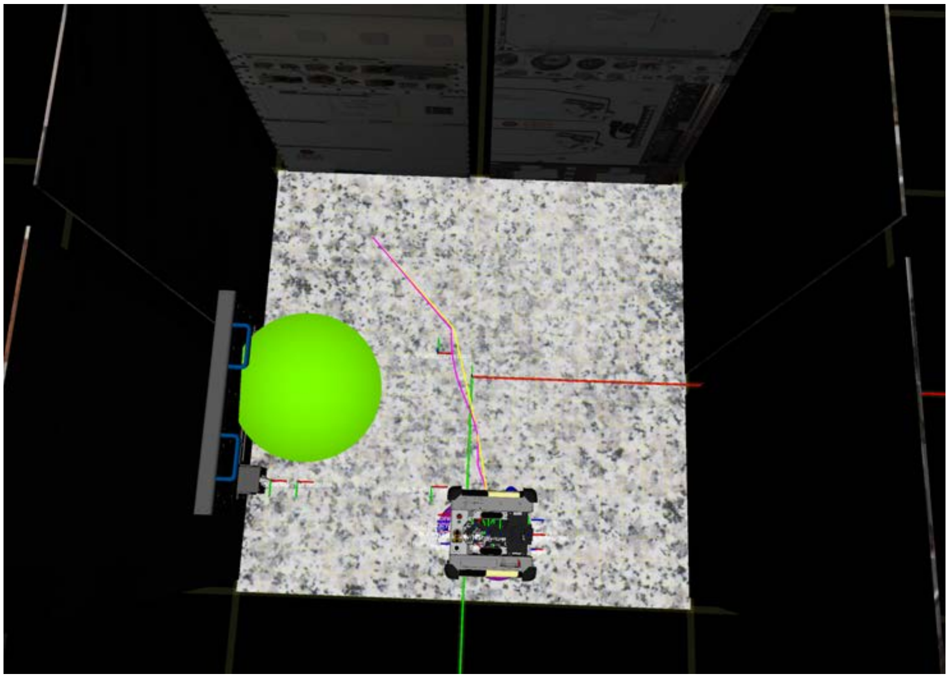

Figure: An example of the on-orbit assembly motion planning algorithm running in simulation (purple and yellow lines) in preparation for ground testing, shown here avoiding a spherical obstacle (green).

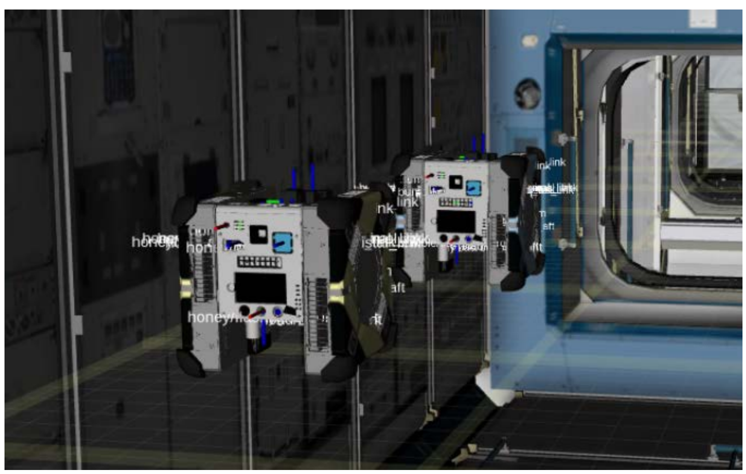

Figure: Leader-follower simulation testing of the DMPC algorithm in simulation (recently tested on-orbit for ReSWARM-2).

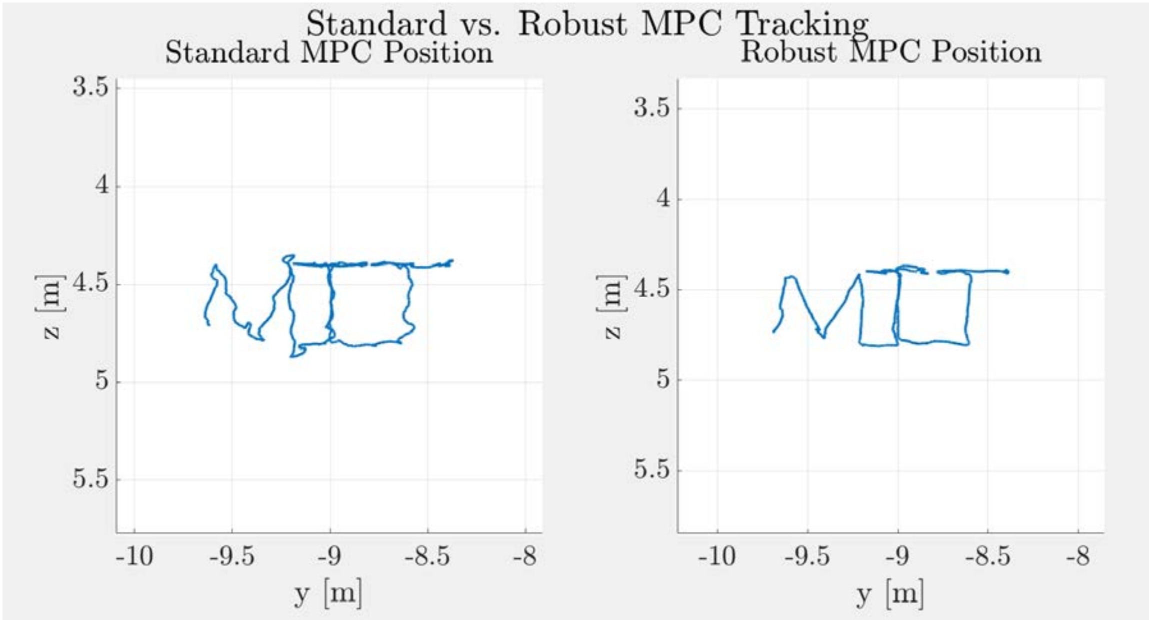

Figure: On-orbit data show the effectiveness of robust control at tracking a reference trajectory with system disturbances. Standard control is shown at left, with robust tracking at right. The reference trajectory in this case spells "MIT."

IV. Near-Term Forward Work, Future Collaboration:

Activities that will occur before the next progress report include the following:

- Post-processing of information-aware planning, on-orbit assembly, and formation flying test data (particularly ReSWARM-2)
- Summary and submission of results in multiple articles: Journal of Field Robotics, IROS RA-L

The SSL/ARCLab has developed a lasting connection with the Ventura group at IST, with research and publications now spanning 3+ years of collaboration. The SSL/ARCLab looks forward to continued collaboration.

V. Interactions with Portuguese Collaborators:

- Weekly virtual meetings with the Ventura group on on-orbit assembly motion planning research
- Dozens of ground test sessions using NASA Ame's Astrobee granite table robotics facility, conducted with virtual Ventura group participation, run in-person by MIT and NASA
- Two successful test sessions on the International Space Station with direct collaboration and participation from the Ventura group
- Multiple virtual conference presentations to robotics researchers, NASA, and others with Ventura group collaborators

- NASA Astrobee Working Group Meetings
- IROS 2021
- ISS Science Symposium

VI. Presentations/Publications/Patents:

[1] K. Albee, M. Ekal, and C. Oestreich, “A Brief Guide to Astrobee’s Flight Software,” November 2021.

[2] M. Ekal, K. Albee, B. Coltin, R. Ventura, R. Linares, and D. W. Miller, “Model Predictive Control and Integration with the Autonomy Stack of the Astrobee Free-Flyer,” in *International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS)*, 2020.

[3] K. Albee, M. Ekal, and B. Doerr, “A Summary of ReSWARM Progress,” Astrobee Working Group Meeting, 2020.

[4] M. Ekal, K. Albee, B. Doerr, P. Roque, R. Ventura, R. Linares “Astrobee Working Group Presentation,” Astrobee Working Group Meeting, 2021.

[5] Pedro Roque, Shahabodin Heshmati Alamdari, Alexandros Nikou, Dimos V Dimarogonas, “Decentralized Formation Control for Multiple Quadrotors under Unidirectional Communication Constraints”, on IFAC2020.

[6] Bryce Doerr, Keenan Albee, Monica Ekal, Richard Linares, Rodrigo Ventura, “Safe and uncertainty-aware robotic motion planning techniques for agile on-orbit assembly”, 31st Annual Space Flight Mechanics Meeting. 2021

[7] Albee, K., Ekal, M., Ventura, R., & Linares, R. (2019). Combining Parameter Identification and Trajectory Optimization: Real-Time Planning for Information Gain. ESA Advanced Space Technologies for Robotics and Automation (ASTRA).

[8] M. Ekal, K. Albee, B. Coltin, R. Ventura, R. Linares, D. W. Miller, “Online Information-Aware Motion Planning with Inertial Parameter Learning for Robotic Free-Flyers,” in *IEEE International Conference on Intelligent Robots and Systems* (IROS), 2021

[9] M. Ekal, K. Albee, B. Doerr, and P. Roque, “MIT/IST/KTH ReSWARM,” presented at Astrobee Working Group Meeting, Fall 2021.

[10] K. Albee, M. Ekal, B. Doerr, and P. Roque, “ReSWARM ISS Symposium Update” presented at ISS Increment 66 Science Symposium, 2021.

Note: multiple additional publications are now in preparation based on ReSWARM-1 and ReSWARM-2 ISS results.