A Three-Finger Gripper Prototype for Autonomous Free-Flying Manipulation of On-Orbit Logistics

Jordan Kam*, Andres Mora†, Brian Coltin‡, In-Won Park‡, Jose Cortez†, Ruben Garcia‡ and Jonathan Barlow‡

*University of California, Berkeley, NASA Ames Research Center, USA

† Millennium Engineering and Integration Solutions, NASA Ames Research Center, USA

‡ KBR Wyle, NASA Ames Research Center, USA

Email: jordan.k.kam@nasa.gov

***Abstract*—Astrobee is a free-flying robot aboard the International Space Station (ISS) that performs autonomous microgravity manipulation tasks such as anchoring onto smooth surfaces and perching onto ISS handrails. Autonomous free-flying intra-vehicular robots that transport cargo could help manage on-orbit logistics for future crewed and uncrewed space stations. However, cargo transport in microgravity presents novel challenges in ensuring contact-rich free-flying manipulation. The authors propose a novel prototype of a three-finger underactuated tendon-driven gripper for Astrobee to manipulate cargo logistics in microgravity. By leveraging Astrobee's reconfigurable perching arm payload, this prototype is capable of contact-rich grasping and transport of a single-size ISS cargo transfer bag (CTB). This article presents the hardware design, gripper prototype, and payload testing at Astrobee's Granite Lab testing facility.**

I. Introduction

Intra-vehicular free-flying robots could close habitat monitoring, maintenance, and logistics management gaps for future on-orbit space stations by using autonomous manipulation [1, 2, 3]. The Astrobee free-flying robot has been performing autonomous on-orbit operations such as Radio-frequency identification (RFID) Enabled Autonomous Logistics Management (REALM), docking, and perching onto the ISS handrails [4, 2, 5, 6]. Novel gripper payloads could enable Astrobee to expand its capabilities to manage on-orbit logistics on the International Space Station (ISS). The same hardware could be extended to the next generation of intra-vehicular free-flying robots aboard future on-orbit space stations. Fig. 1 presents the workflow of Astrobee reducing cargo logistics on the ISS by leveraging autonomous transporting.

On the ISS today, cargo transfer bags (CTBs) ranging from half-size to triple-size are the way cargo (i.e. science experimentation, flight hardware, and clothing) is stored and transported. Transporting these ISS CTBs becomes difficult as their soft-body handles have unknown dynamics in microgravity that depend heavily on the CTB's inertial properties [7]. Rigid grippers with more surface area coverage and claw-like grip could allow for robust contact-rich free-flying cargo manipulation [8].

II. Gripper Prototype for Logistics

The gripper prototype is a rigid three-finger underactuated tendon-driven gripper mechanically designed to be installed into Astrobee's perching arm payload. Using the modular wrist mount of the perching arm, the three-finger gripper prototype seamlessly integrates into a 2 degree-of-freedom (DOF) arm payload that can grasp without modification to Astrobee's flight manipulation software [9]. This gripper prototype was designed for Astrobee integration simplicity, surface contact-rich distal joints, and constraint to Astrobee's 123.2 × 152.4 × 101.6 mm (4.85 × 6.0 × 4.0 in.) payload bay volume [6]. Adapting a claw-like grasp, the gripper could grasp onto the soft handles of an ISS CTB and transport it between station modules. Fig. 2 shows the manufactured three-finger prototype next to its computer-aided design (CAD) model.

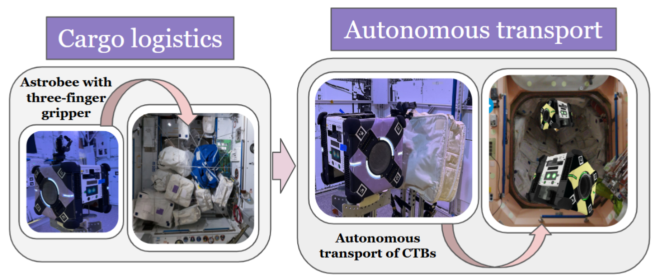

Fig. 1. Workflow of Astrobee reducing cargo logistics using manipulation.

III. Granite Lab Test Setup

To test the gripper's capabilities in logistics management, a single-size ISS CTB model is used as a case study. Fig. 3 shows Astrobee grasping a single-size ISS CTB model with the three-finger prototype while free-flying on the granite table. Hardware-in-the-loop (HIL) ground testing is performed at the Granite Lab testing facility at NASA Ames Research Center to simulate microgravity affects while Earth. Astrobe

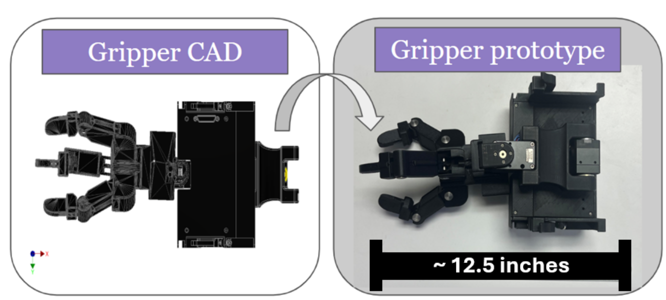

Fig. 2. Three-finger gripper CAD model next to the manufactured prototype.

Fig. 3. Astrobee grasping an single-size ISS CTB with the three-finger prototype while free-flying on the granite table.

and the single-size ISS CTB are both mounted on separate air carriages to give each body a 3-DOF free-flying affect. To test and demonstrate control and localization capabilities while grasping the CTB, a series of predefined segments of way points, also known as an Astrobee Plan or fplan is executed while on the granite table. For this test, the `granite_square.fplan` is executed to test Astrobee's CTB grasping capabilities in different locations on the granite table while flying. The plan commands the Astrobee robot to follow a square pattern of approximately $50cm$. During this granite test, we monitored the Astrobee's position to see how it reacted to grasping the CTB. Fig. 4 shows the Astrobee `granite_square.fplan` flight trajectory on the granite table with the corresponding frames for Astrobee relative to the granite table.

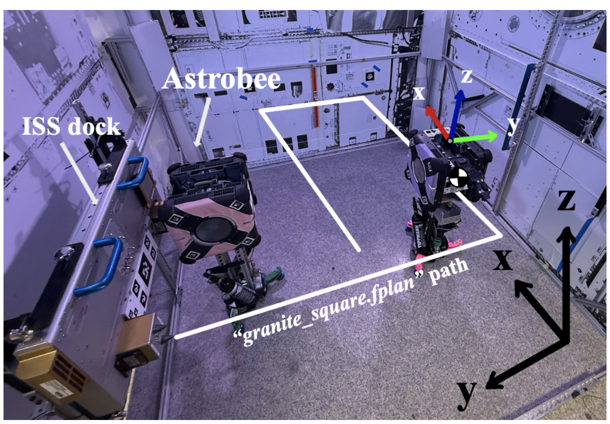

Fig. 4. Astrobee flying the `granite_square.fplan` in the Granite Lab.

IV. Results

Fig. 5 shows the time-series data of Astrobee's position in the Granite Lab (X, Y, Z) during the `granite_square.fplan` flight. Astrobee's x-position noise exhibits the largest variation during flight, initially retracting to approximately $-0.6m$ before rapidly extending to nearly $0.8m$. The y-position noise shows moderate fluctuations around $0.5m$, suggesting minor lateral corrections during flight. The z-position remains relatively stable throughout the sequence, since the granite lab cannot test in all 6-DOF holonomic motion that Astrobee could replicate on station. Overall, although there is some noise variation in

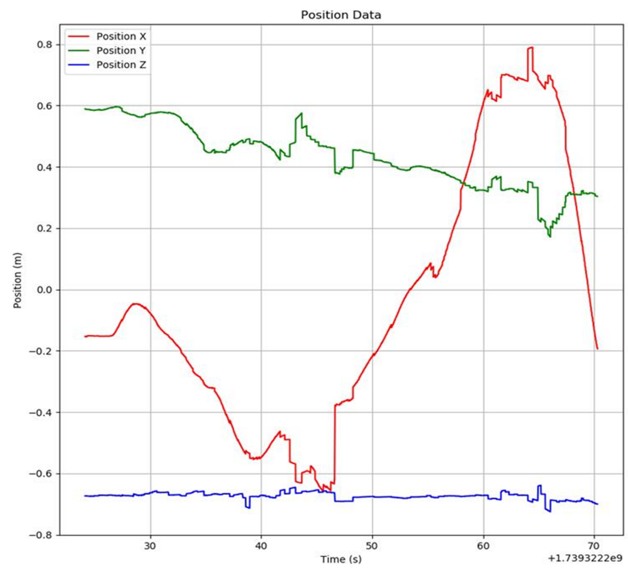

Fig. 5. Astrobee position executed during the `granite_square.fplan` plan grasphing a ISS CTB with the three-finger gripper prototype.

the data, the prototype is capable of keeping Astrobee on the planned trajectory while grasping the single-size ISS CTB while free-flying.

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