Autonomy for Lunar Surface Infrastructure Construction

John R. Cooper[1], Irina Kostitsyna[2], Olivia Irene B. Formoso[3], Dominic R. Bisio[1], Joshua N. Moser[1], Matthew P. Vaughan[1], and Matthew K. Mahlin[4]

I. INTRODUCTION

An autonomous system architecture for robotic construction of lunar surface infrastructure is presented. Infrastructure is key to a permanent human presence on the moon. Structures such as launch and landing facilities, environmental shelters, and tall towers to support solar panels or communications equipment will support astronaut activities. An economical way to establish infrastructure is through autonomous robotic construction. A team of robots with various capabilities would transport materials from a lander to a prepared construction site, manipulate structural components for alignment, and actuate tools for joining the structure. After establishing basic truss structures, the robot team would then outfit the structures with cable harnesses for power and data transfer, flexible hoses for fluid transfer, panels (e.g., solar panels, radiators, walls), regolith coverings for radiation mitigation, and other functional modules.

NASA has recently invested in both orbital and surface assembly technologies. The Precision Assembled Space Structure project demonstrated autonomous assembly of a modular space structure using a general purpose robotic manipulator [2]. The Tall Lunar Tower project showed a method to construct vertical structures using a pair of manipulators and an intelligent jig [6]. The Automated Reconfigurable Mission Adaptive Digital Assembly Systems project developed a system to assemble arbitrary 3D structures with a team of purpose-built inchworm robots that travel along the structure itself [3].

Figure 1 shows a conceptual moon base enabled by the architecture presented herein. This concept is achievable within a few years by leveraging the previous technology developments and industry partners with space-qualified robotics.

Figure 2 shows the system architecture for the autonomy and robotics needed to construct lunar surface infrastructure. The elements in Figure 2 are categorized as Mission-Level Autonomy, Agent-Level Autonomy, and Robotics Segment. Mission-Level Autonomy elements are centralized, make use of global information, and act on all robots in the team. Agent-Level Autonomy elements act on individual robots using local information. Robotics Segment elements represent the physical robot hardware.

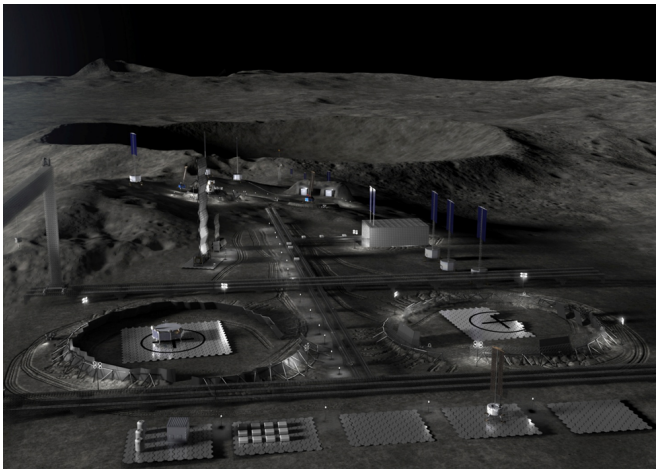


Fig. 1. A conceptual robotically constructed moon base

The human input to the system is a Mission Definition, which consists of a list of tasks. The ultimate output is physical pose of structural and outfitting components as they are manipulated and assembled.

II. TASK ALLOCATION AND SCHEDULING

The Task Allocation and Scheduling element ingests the mission definition and the global state and determines a sequence of tasks and assignment of tasks to agents. Each task is composed of coordinates, task constraints (e.g., precedence of other tasks in the mission), agent constraints (e.g., what capabilities must an agent have to perform the task), and the action to perform at the coordinates. When a new task is assigned, a new goal state is communicated to the assigned robot. Task allocation and scheduling can be achieved via discrete optimization methods such as mixed integer programming and reinforcement learning.

III. MOTION PLANNERS

Motion planning is divided between global and local elements. The Global Motion Planner generates coarse, deconflicted waypoints for all agents simultaneously while the Local Motion Planner connects the global waypoints using the local information for individual robots.

The Global Motion Planner uses coordinates of the currently assigned task, along with a world model, and generates agent workspace paths for the Local Motion Planner. Additionally, the Global Motion Planner gets feedback on the success of the Local Motion Planner to determine if

[1]Autonomous Integrated Systems Research Branch, NASA's Langley Research Center, Hampton, VA 23681, USA

[2]KBR, Inc., Coded Structures Lab, NASA Ames Research Center, Moffett Field, CA 94035, USA

[3]Coded Structures Lab, NASA Ames Research Center, Moffett Field, CA 94035, USA

[4]Structural Mechanics and Concepts Branch, NASA's Langley Research Center, Hampton, VA 23681, USA

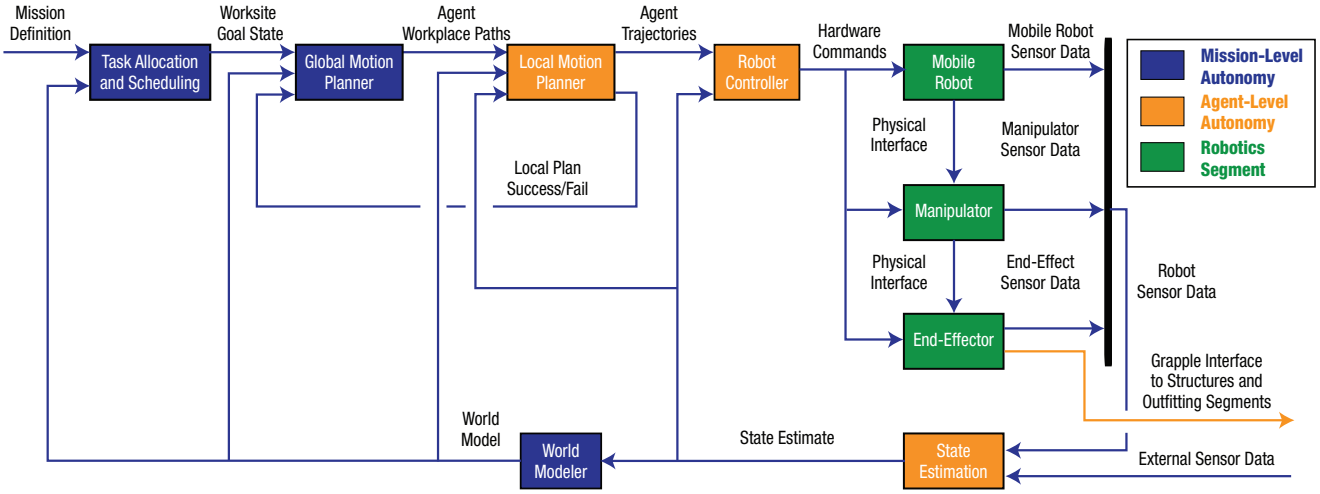


Fig. 2. Autonomy and robotics block diagram for construction of lunar surface infrastructure

replanning is needed. The Global Motion Planner makes use of sample-based motion planning algorithms such as rapidly-exploring random trees (RRT) and its optimizing variant, RRT* [5], [4].

The Local Motion Planner also uses sample-based motion planning, but with a shorter step size between waypoints. The local waypoints are then connected via a time-parameterized curve to generate dynamically feasible trajectories.

IV. ROBOT CONTROLLER

A virtual leader control algorithm is used for trajectory tracking [1]. A virtual robot (the leader) travels with its motion constrained to the planned trajectory. The virtual leader's speed is driven by two terms: one driving it toward the end of the spline and another slowing it down so the real robot does not lag too far behind. The real robot is controlled with a feedforward term equal to the virtual leader's velocity and a feedback term driving the error between the virtual leader and real robot states to zero.

Visual servoing is used for fine alignment of parts to be joined. Images from a camera on the End-Effector are used to estimate the relative pose between the End-Effector and the object it needs to interact with (e.g., a structural element).

The two modes of motion for robots are gross motion and fine alignment. Gross motion refers to long range movements where collision avoidance is required, while fine alignment occurs within a small region around a goal state using local information to correct for uncertainties. The virtual leader algorithm is used for gross motion while the visual servo algorithm is used for fine alignment. Both modes are augmented by admittance control which uses a force/torque sensor attached to the End-Effector to ensure the robot never exerts undesired loads on the structure and can follow guide features during fine alignment [7].

V. STATE ESTIMATION AND WORLD MODELER

The State Estimation Element uses the onboard sensors of each robot to estimate robot poses and velocities, poses of target objects in the environment (i.e, structural or outfitting components), and the state of static environment features.

A continuously updated, centralized representation of the environment is maintained by the World Modeler element by combining the local state estimates. The centralized world model is propagated forward to use for motion planning.

VI. ROBOTICS SEGMENT

The robotics segment is divided into three elements. The Mobile Robot fulfills the function of transporting structural and outfitting components to and around the construction site. The Manipulator places and aligns components in six degrees of freedom in preparation for joining. The End-Effector contains tools and sensors for actuating and verifying the joining of structural and outfitting components.

REFERENCES

[1] David Bacher, John R Cooper, and Javier Puig Navarro. Trajectory generation with load constraints for robotic manipulators. In *ASCEND 2023*, page 4664. 2023.

[2] John R Cooper, Collin J Cresta, Thea V Avila, Radhika Rajaram, Andrew K McQuarry, Jacob Martin, and Olive R Stohlman. Test results for autonomous assembly of modular space structures. In *ASCEND 2023*, page 4699. 2023.

[3] Christine E Gregg, Damiana Catanoso, Olivia Irene B Formoso, Irina Kostitsyna, Megan E Ochalek, Taiwo J Olatunde, In Won Park, Frank M Sebastianelli, Elizabeth M Taylor, Greenfield T Trinh, et al. Ultralight, strong, and self-reprogrammable mechanical metamaterials. *Science robotics*, 9(86):eadi2746, 2024.

[4] Sertac Karaman, Matthew R Walter, Alejandro Perez, Emilio Frazzoli, and Seth Teller. Anytime motion planning using the rrt. In *2011 IEEE International Conference on Robotics and Automation*, pages 1478–1483. IEEE, 2011.

[5] Steven M LaValle and James J Kuffner Jr. Randomized kinodynamic planning. *The international journal of robotics research*, 20(5):378–400, 2001.

[6] Jacob Martin, Iok M Wong, Kyongchan Song, Matthew K Mahlin, Derrick Seubert, John R Merila, Caden Knutsvig, and Amy Keller. Hardware systems and edu demonstration of the tall lunar tower project. In *AIAA SCITECH 2025 Forum*, page 0404, 2025.

[7] Guillaume Morel, Ezio Malis, and Sylvie Boudet. Impedance based combination of visual and force control. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146)*, volume 2, pages 1743–1748. IEEE, 1998.