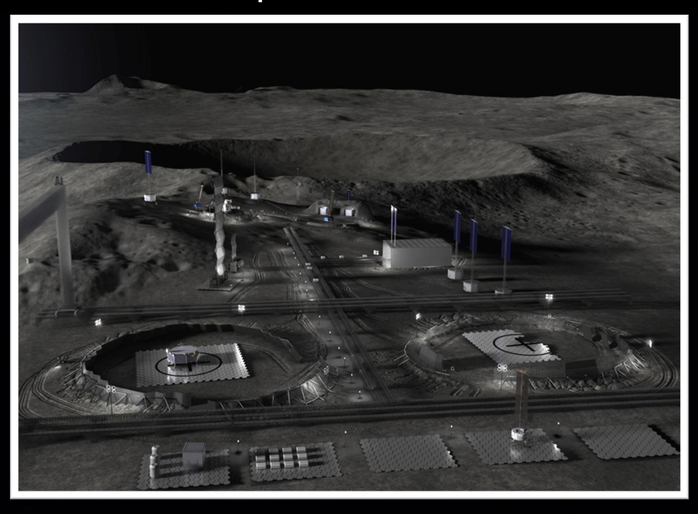
Autonomy for Lunar Surface Infrastructure Construction

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

[1] NASA Langley Research Center, [2] NASA Ames Research Center, [3] KBR, Inc.

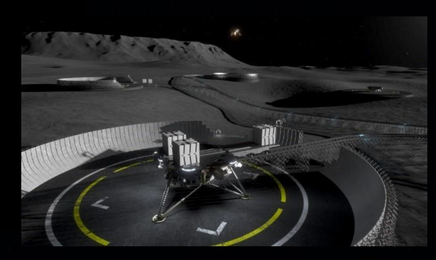
Conceptual Moon Base

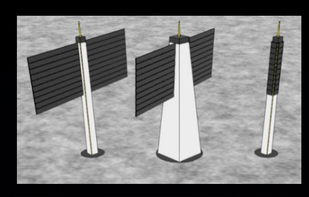


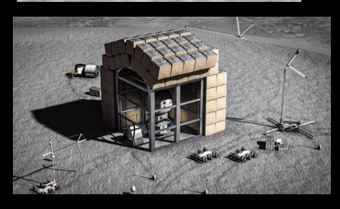
- **Infrastructure** is key to a permanent **Moon Base**
- **Autonomy and Robotics** enable infrastructure construction
- Tasks include:
  1. Site preparation
  2. Offloading materials from lunar landers
  3. Transport materials from lander to work site
  4. Assemble structures
  5. Outfit structures with cabling, hoses, panels, and regolith covering

Key Infrastructure Types:

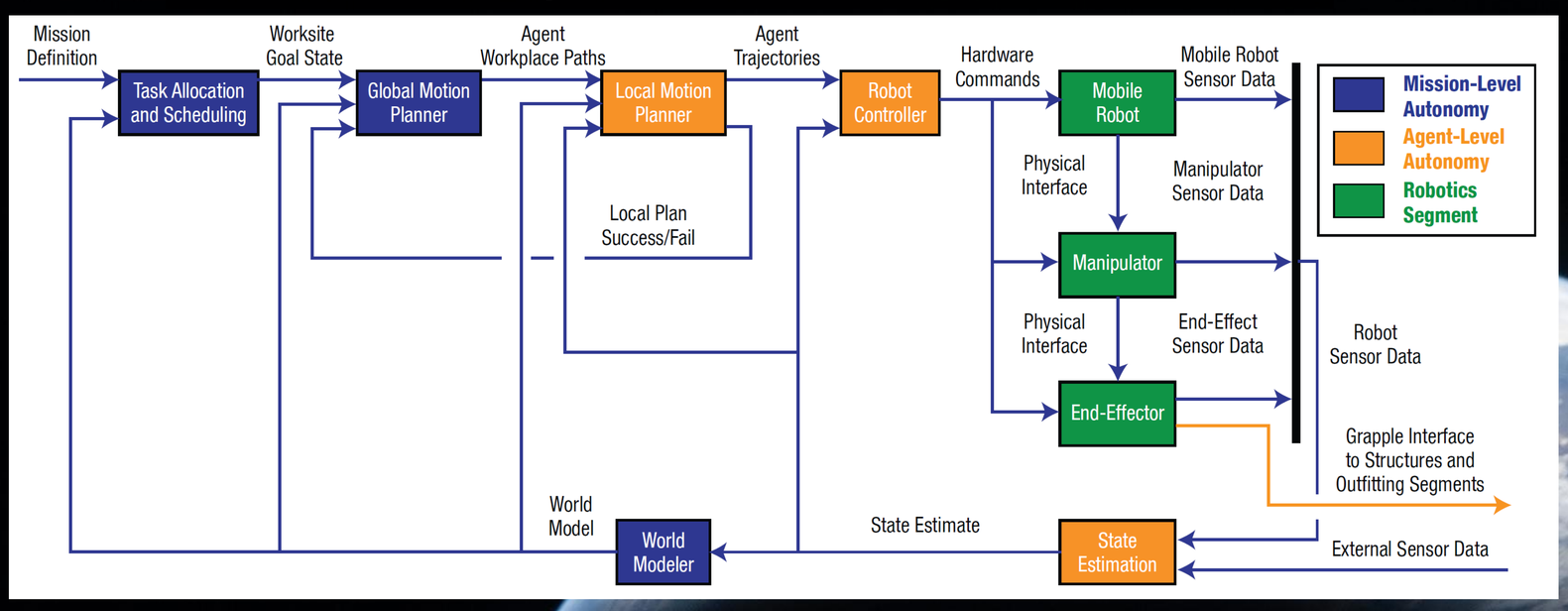
1. Launch & Landing Facility
2. Shelters
3. Towers







Autonomy and Robotics Architecture



Task Allocation & Scheduling

- Mission-level autonomy
- Can be formed as Markov Decision Process
  - State: task status (actively being worked or not), agent status (current task assignment)
  - Action: mapping of agents to tasks in queue
  - Reward: total construction time, total energy used
- Solution methods: reinforcement learning, dynamic programming
- Other frameworks: mixed integer programming



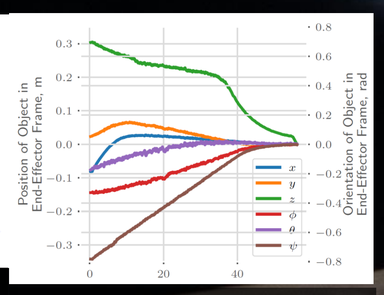
NASA Langley MACRO lab featuring multiple robotic platforms representative of lunar surface construction tasks

Motion Planning and Control

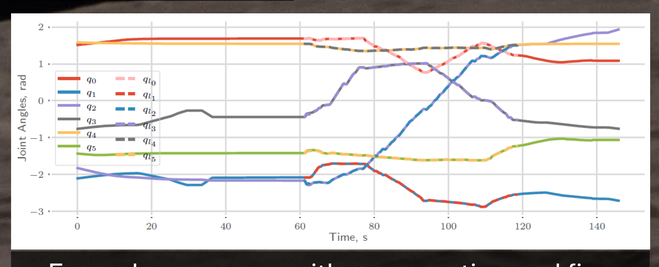
- Global Motion Planner – generate coarse, de-conflicted waypoints for all agents simultaneously
- Local Motion Planner – connect global waypoints using local information for individual robots
- Use sample-based motion planning (RRT*) [4,5]
- At local level, connect waypoints via spline
- Robot control divided into two categories:
  1. Gross motion – track planned path from one task location to the next
     - Virtual leader control [1]
  2. Fine alignment – correct for uncertainties in world model to interact with objects and payloads
     - Visual servoing
     - Impedance/admittance control allows robot to follow guide features [7]



2D Visualization of RRT* algorithm



Visual servoing example



Example maneuver with gross motion and fine alignment including virtual leader tracking

Robotics Elements

- Mobile Robot
  - Ability to transport structural and outfitting components to and around construction site
  - Examples: rover, inchworm
- Manipulator
  - Ability to place/align components in six degrees of freedom in preparation for joining
- End-Effector
  - Tools and sensors for actuating and verifying joining



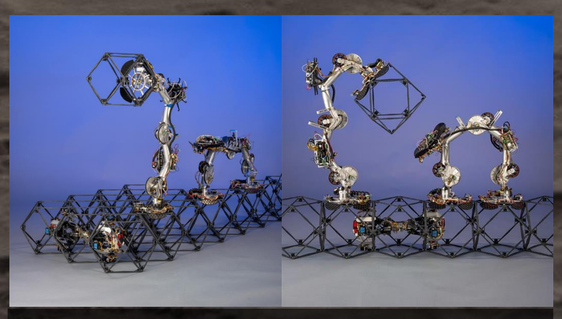
NASA's Precision Assembled Space Structure [2]

State Estimation/World Modeling

- Individual agents estimate their own pose and velocity + poses of target objects in the environment + state of static environment features
  - Kalman filter-based approaches
  - SLAM
- Individual state estimates combined at the mission-level into a world model used for motion planning

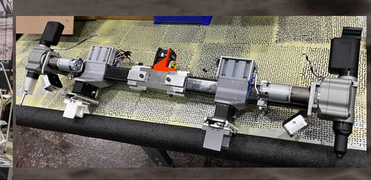


SLAM map from mobile robot

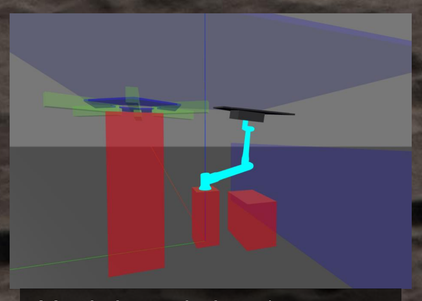


NASA's Automated Reconfigurable Mission Adaptive Digital Assembly System [3]





NASA's Tall Lunar Tower project [6]



Mesh-based planning scene

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