LunAR-X: Autonomous Lunar Excavation Robot

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Sponsors: Red Whittaker and Caterpillar

Objective

Problem Statement

- Future human research bases and settlements on the Moon require extensive infrastructure
- Space construction is dangerous, inefficient and exhausting for humans, we require robotic solutions

Challenge: The plume and exhaust from landing spacecrafts can damage infrastructure near the landing pads. How do we avoid this?

Solution: Build berms (raised mounds of lunar regolith/ sand) around the landing pad to contain/divert the plumes.
- Using Bucket-drum mechanism designed by NASA for low-gravity excavation

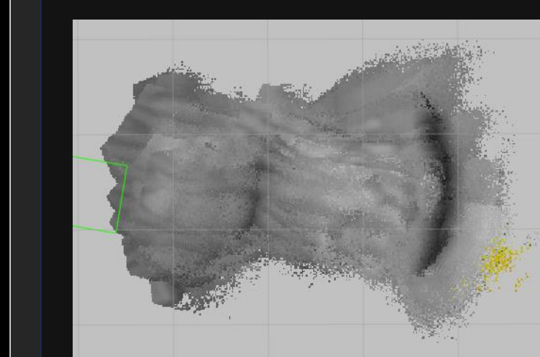
Use Case

- Operator gives goal
  - Height and length of desired berm
  - Location of construction
- Robot starts autonomous construction cycle
  - Excavate
  - Transport
  - Deposit
- Robot evaluates the construction at the end

Perception & Mapping

Point Cloud

- Pointcloud transformed from camera frame to base link frame
- Points corresponding to the excavation tool cropped out and filtered
- Tool distance from the ground estimated using the elevation of points directly under the tool

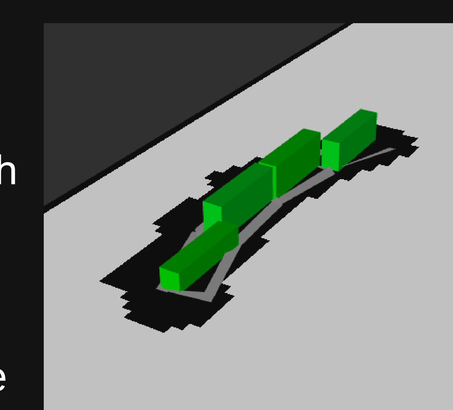


Map

- Elevation map needed for berm evaluation
- Local elevation map constructed in patches of 1.5 x 1.5cm
- Fused with global elevation map using a Bayes filter to smoothen
- Navigation costmap built with high cost for regions around obstacles, boundaries and constructed berm

Berm Evaluation

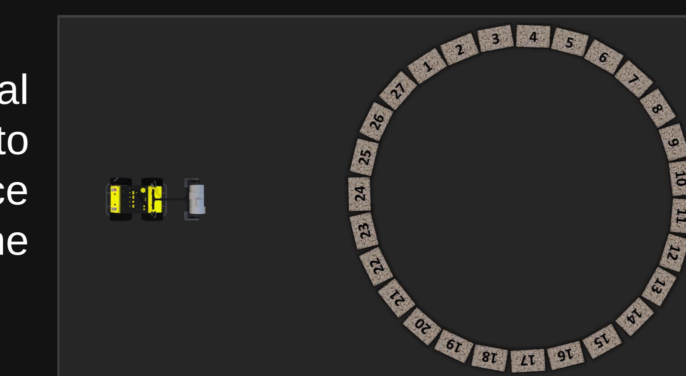
- Evaluation of the constructed berm
- 95th percentile elevation calculated to get berm height of each section
- Peak-line points counted using elevation binning to get berm length
- Elevations across berm sections summed to get berm volume



Task Planning

Problem Formulation

Find a feasible and optimal sequence of berm sections to visit, minimizing overall distance travelled or time taken during the entire operation



Graph Representation

- **Node**: Vector of visited sections and robot pose configuration
- **Edge**: Navigation from excavation region to berm section and back
- **Goal Condition**: Visit all berm sections

Solution Approach

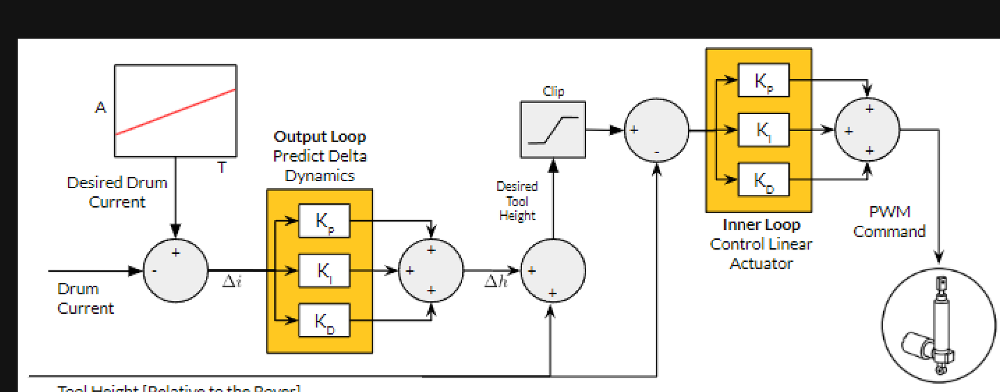
- **High-level**: A* search with edge costs derived from low-level optimization, utilizing a TSP solver as a heuristic
- **Low-level**: Calculate edge cost using Hybrid A* with motion primitives to address for kino-dynamic constraints

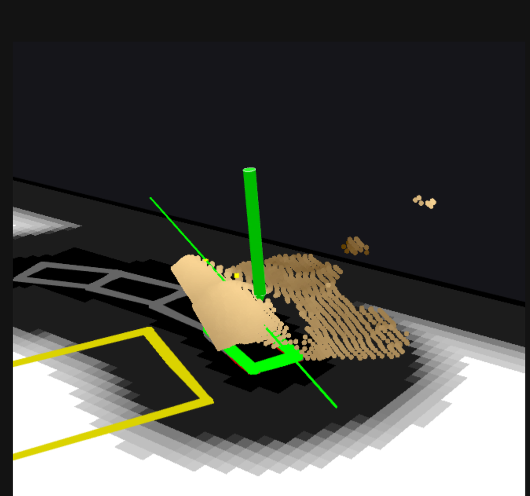
Tool Control

AutoDig

Challenge: How to ensure the correct excavation depth while moving over uneven terrain?

- Feedback from tool motor current commands tool height for efficient excavation
- Cascaded PID loop controls the excavation depth
  - Outer Loop: Predict change in height given error in tool current
  - Inner Loop: Moves the tool to the given desired tool height





AutoDump

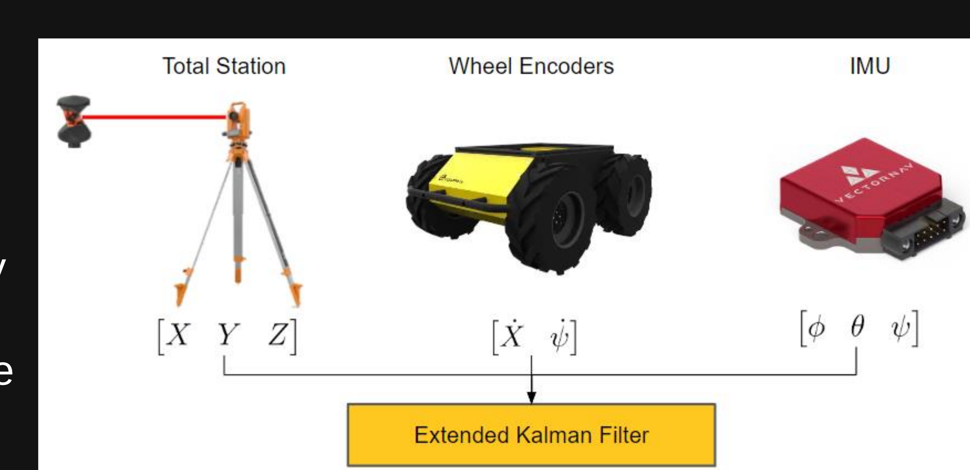
Challenge: How to ensure precise material deposition despite the possibilities of navigational errors?

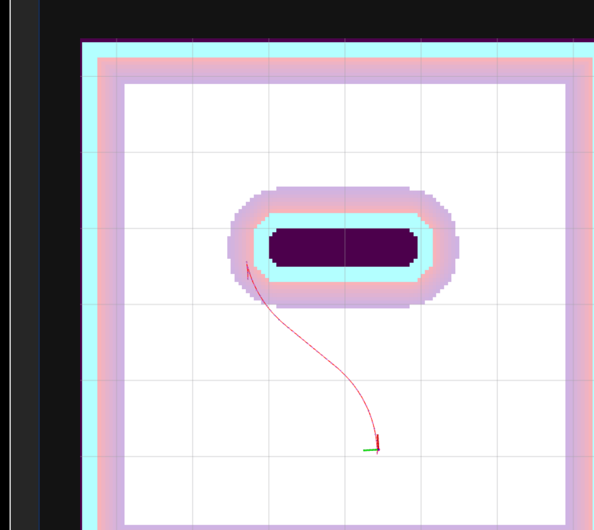
Use the point cloud to segment and detect the peak line of the previously built berm
- Compute error from the desired dump position and orientation of the tool
- Correct position and orientation by visual servoing

Localization & Navigation

Localization

- Total Station used as absolute position sensor
- IMU used to estimate absolute orientation
- Wheel encoders used for velocity inputs
- Offset between total station frame and IMU frame calibrated online when traversing in a straight line





Navigation

Challenge: How to traverse in deformable sandy terrain with high motion resistance, no point turns and no precise control possible?

Use Hybrid A* with Motion Primitives
- Path planning with kino-dynamic constraints
- Regulated Pure Pursuit for path tracking
- Correct for final yaw error using direct PID control

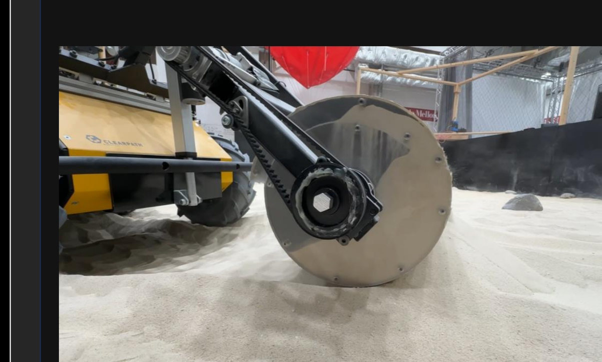
System Capabilities

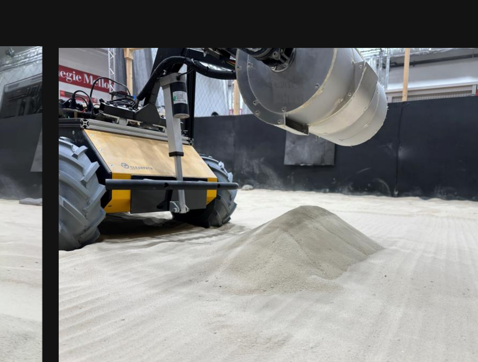
Performance

The system can:
- Build a berm 15 cm tall and 1.6 m long in ~30 mins
- Excavate, transport and deposit 7-9 kg (15-20 lbs.) of sand every cycle
- Map the berm being constructed
- Evaluate constructed berm
- Operate without human intervention
- Build a curved berm, with 2 m radius

Limitations

- Construction limited to a berm height of 20 cm
- Berm length only limited by amount of sand and battery life
- Current operational battery life limited to 1 hour





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