CraterGrader: Autonomous Lunar Sitework Robot

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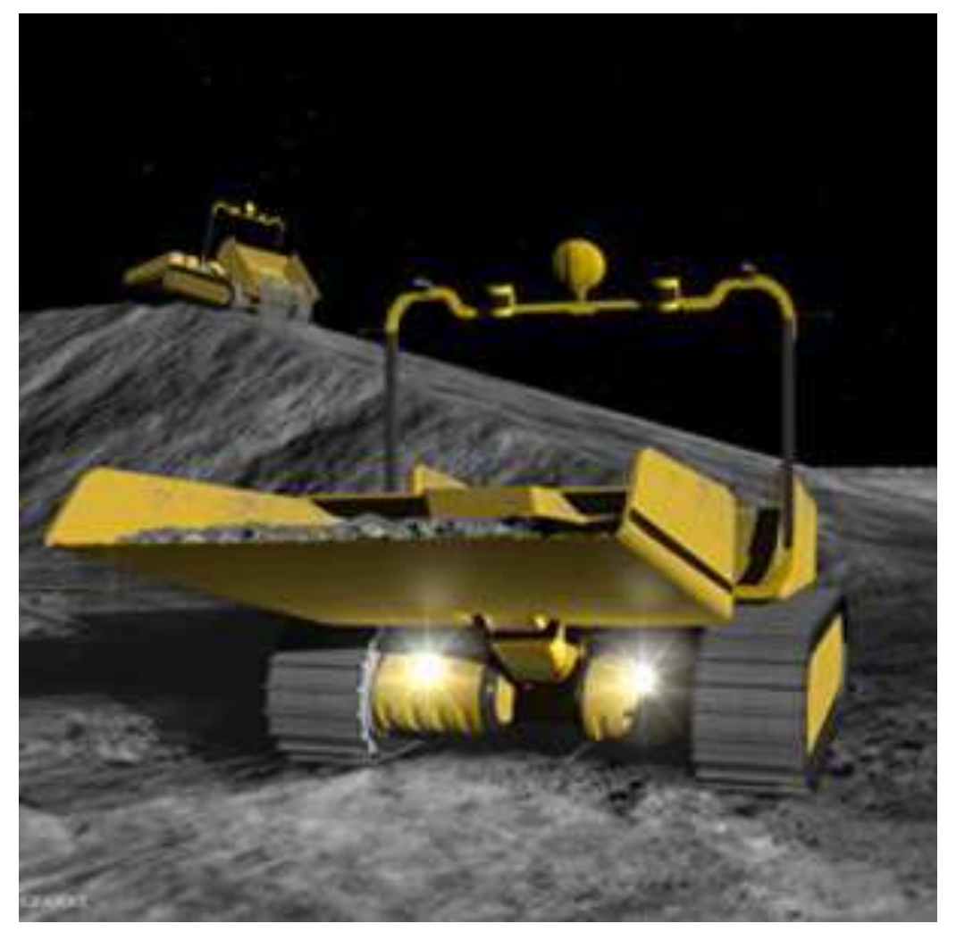
Problem Statement & Mission / Use Case

NASA and commercial partners are highly interested in lunar sitework
- Recent proposals are requesting autonomous solutions for lunar sitework [1]
- Motivating use cases include landing pads, roads, and foundations

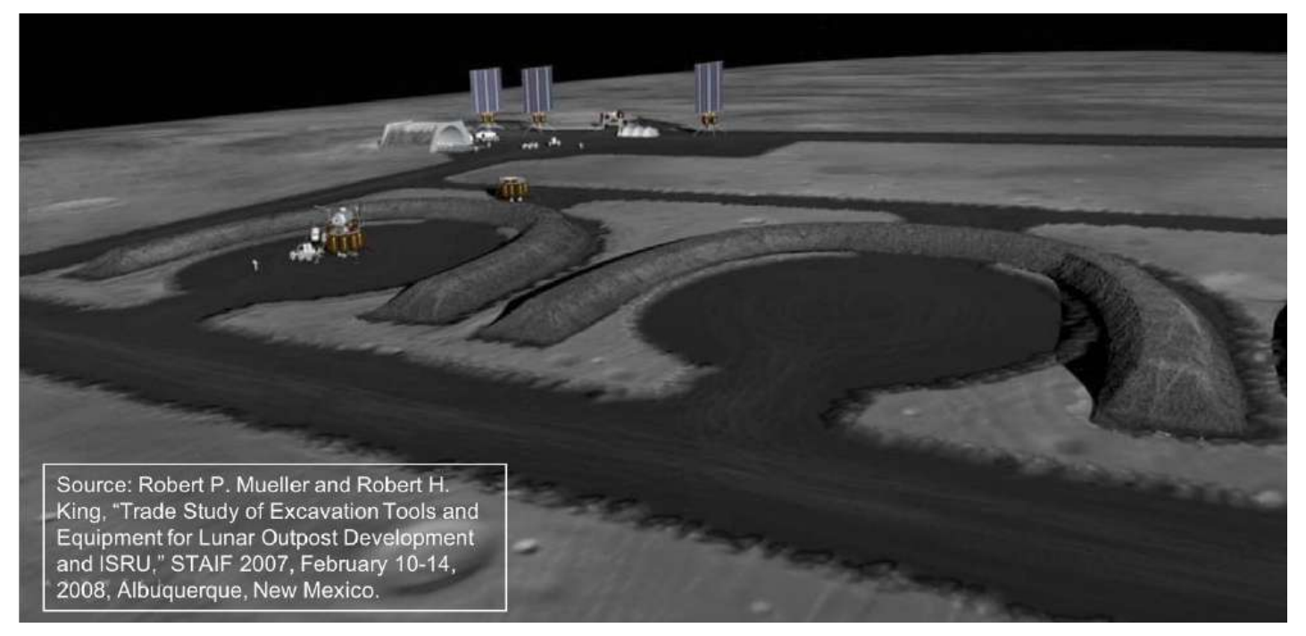
Terrestrial grading has a long heritage, rooted in large mass and energetics
- Standard grading blade smoothes as the final stage of sitework
- Vast majority of motor graders are operated manually, relying directly on experience and operator line of sight

There is a strong need for the development of lunar surface grading/smoothing autonomy, extending from Earth-based priors
- Use case: team of users sets up a robotic worksite around arbitrary terrain and specifies a target map for desired terrain post-manipulation
- User sends a signal from operations computer to engage autonomy
- Robotic platform in worksite maps the worksite terrain
- Users watch mapping updates and monitor system health
- Robotic platform finishes initial map and begins manipulating terrain
- After eventual manipulation, terrain is within specs, and work stops



Source: [space.com - Lunar Bulldozer]

Source: [im-mining.com - Cat® 24 Motor Grader]



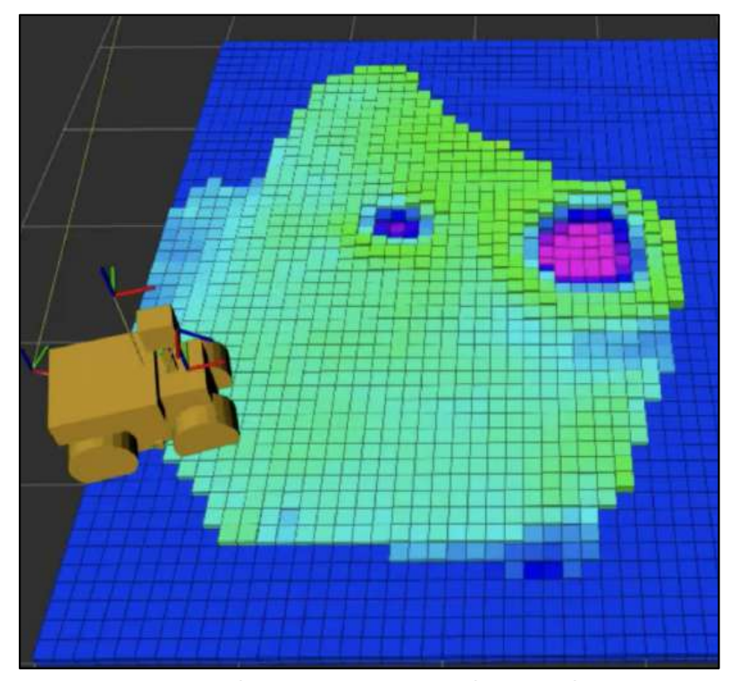
Source: Robert P. Mueller and Robert H. King, “Trade Study of Excavation Tools and Equipment for Lunar Outpost Development and ISRU,” STAIF 2007, February 10-14, 2008, Albuquerque, New Mexico.

Source: [ucf.edu - ISRU for Mitigating Plume Effects]

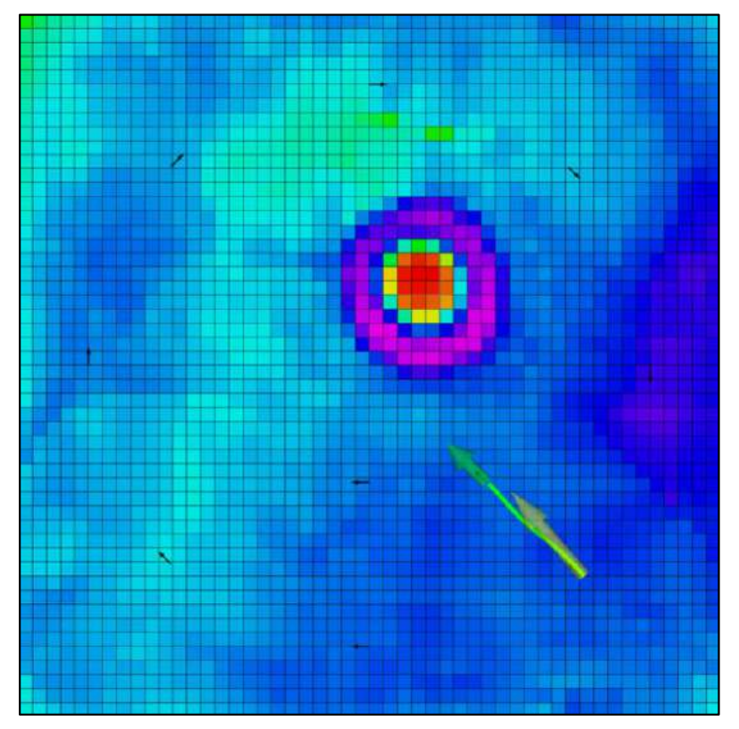
Perception & Mapping

Point Cloud Processing at the Heart of Perception
- Raw point cloud representation of terrain retrieved from stereo camera
- Point cloud is filtered, downsampled
- Non-worksite data removed with 2D box filters

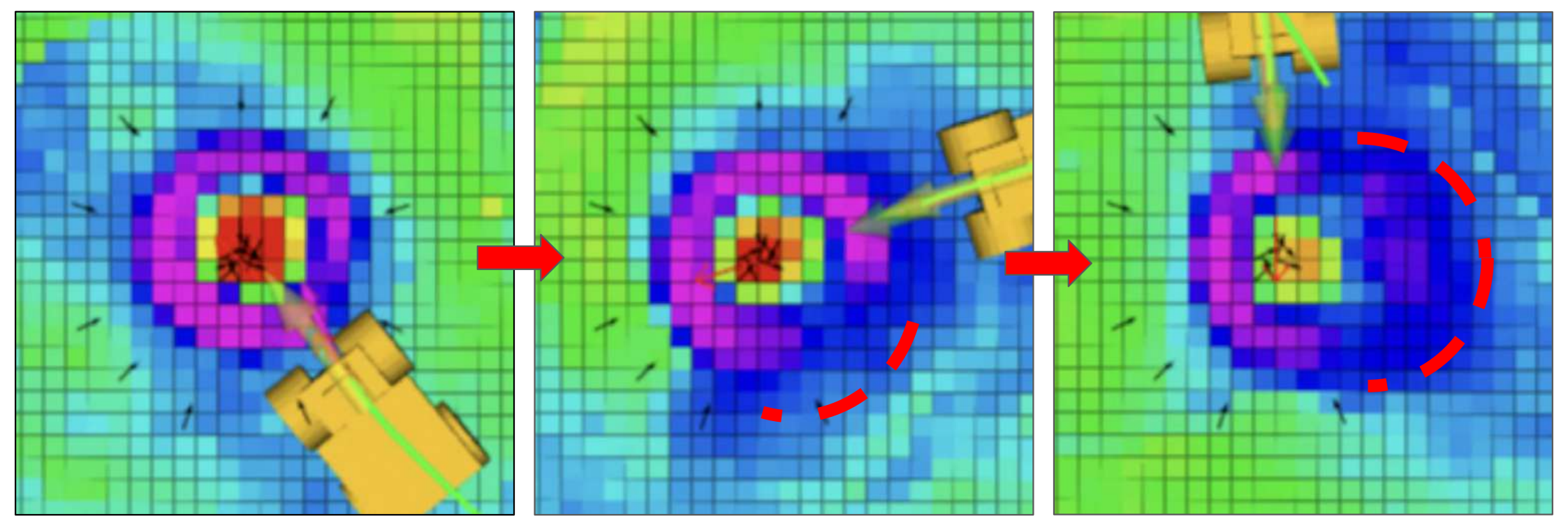
Mapping Topography Representations for Earthmoving
- 2.5D height map representation: global map discretized into 2,500 10cm x 10cm grid cells representing terrain height
- Constantly changing topography requires worksite map to be updated as robot manipulates terrain
  - Dynamic terrain updates leveraging a Bayesian filtering approach
  - Each grid cell encodes 1D Kalman filter, providing height estimate and variance at that cell
- Robot tracks grid cells seen vs. not seen during initial exploration phase
- Worksite normalization post-exploration adjusts grid cell height distribution
- Smoothing kernels enable attenuation of high frequency terrain variations
- Noise injection for knowingly manipulated cells allows for fast dynamic updates



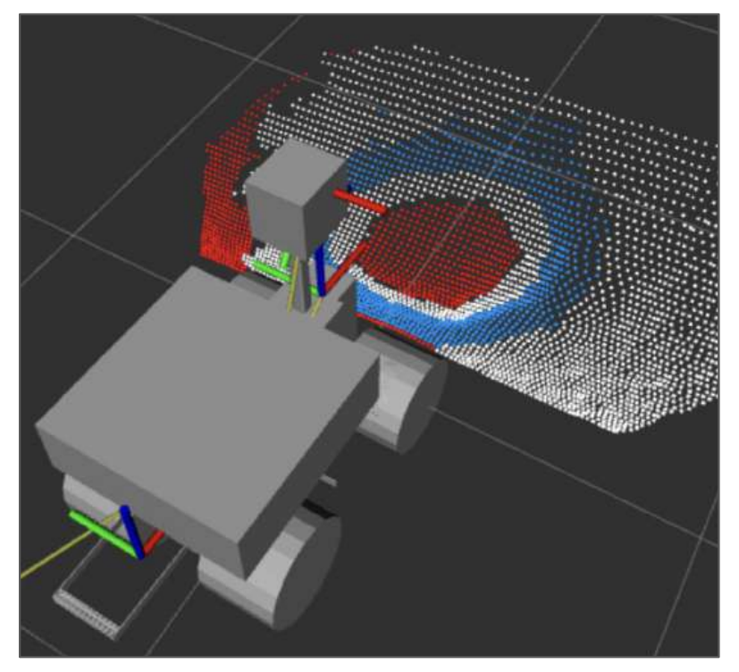
Discretized 2.5D Vertical Height Map



Post-Exploration Normalized Worksite Map



Counter Clockwise Grading Mapping Update as a Function of Time



Above/Below-Ground Plane Segmentation

Planning

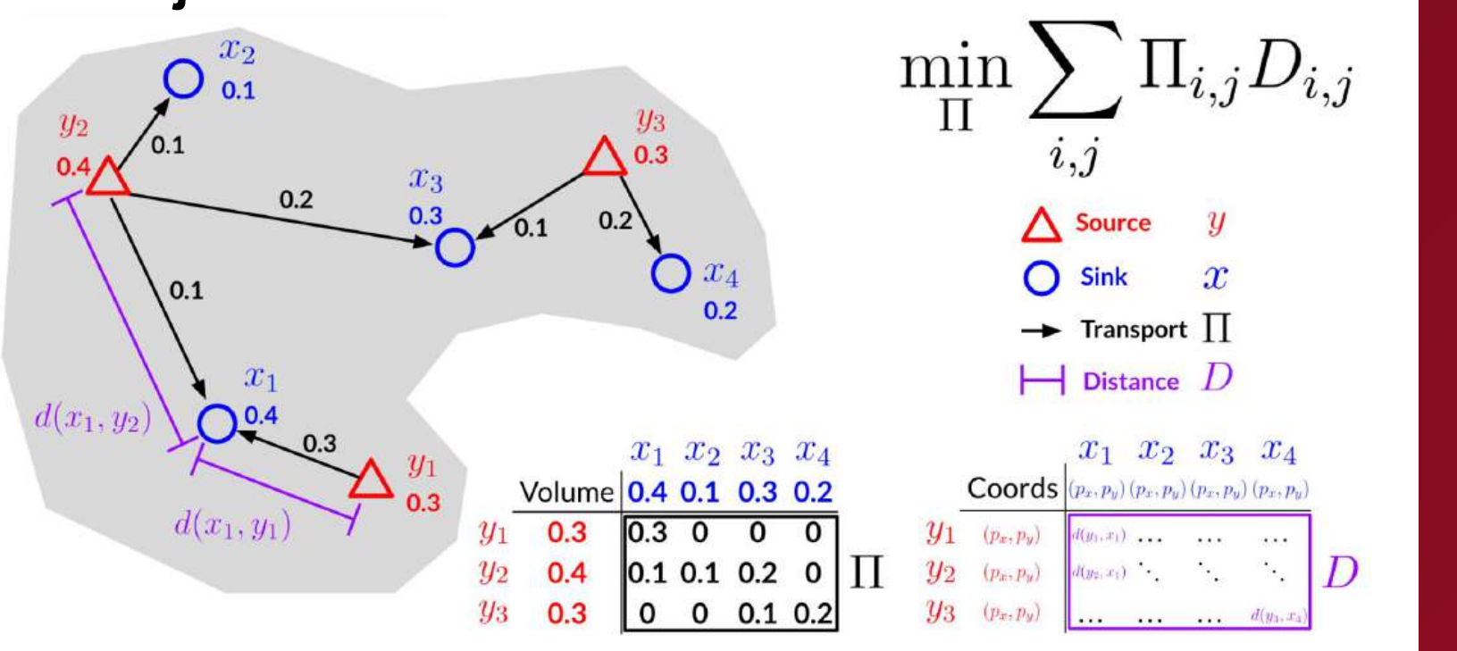
Task Planning as Optimal Transport
- Discretized height map converted into a graph, formulated as Earth Mover’s Distance [2] problem:
  - Nodes defined as high/low terrain regions, parametrized by material volume and max/min height point from global fit plane
  - Edge weights defined as traversal cost between node extrema

Tool Planning as Reactive Heuristic
- Simple drive-direction heuristic for tool position

Kinematic Planning Considers Vehicle Constraints
- Lattice A* search, penalizing driving over high/lows
- Dynamically updated search parameters and thresholds to ensure path finding in near real time

Behavior Planning
- Robust finite state machine, allowing clean transition between exploration & transport phases
- Monitor system state, triggering necessary replans

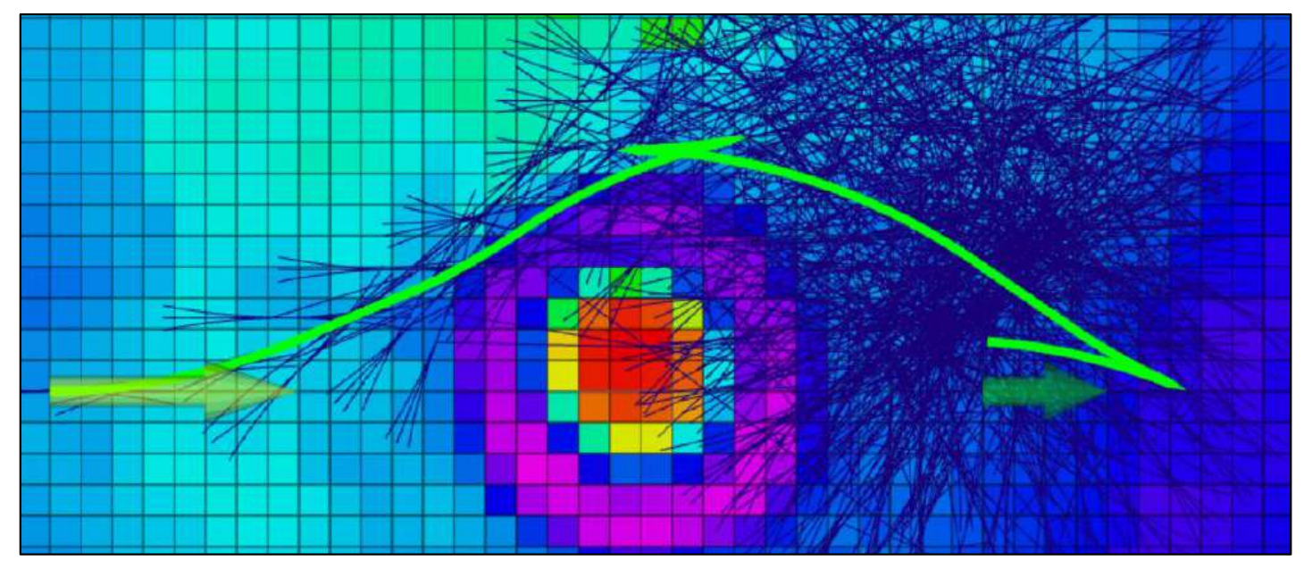
Objective: Minimize Volume Moved x Distance



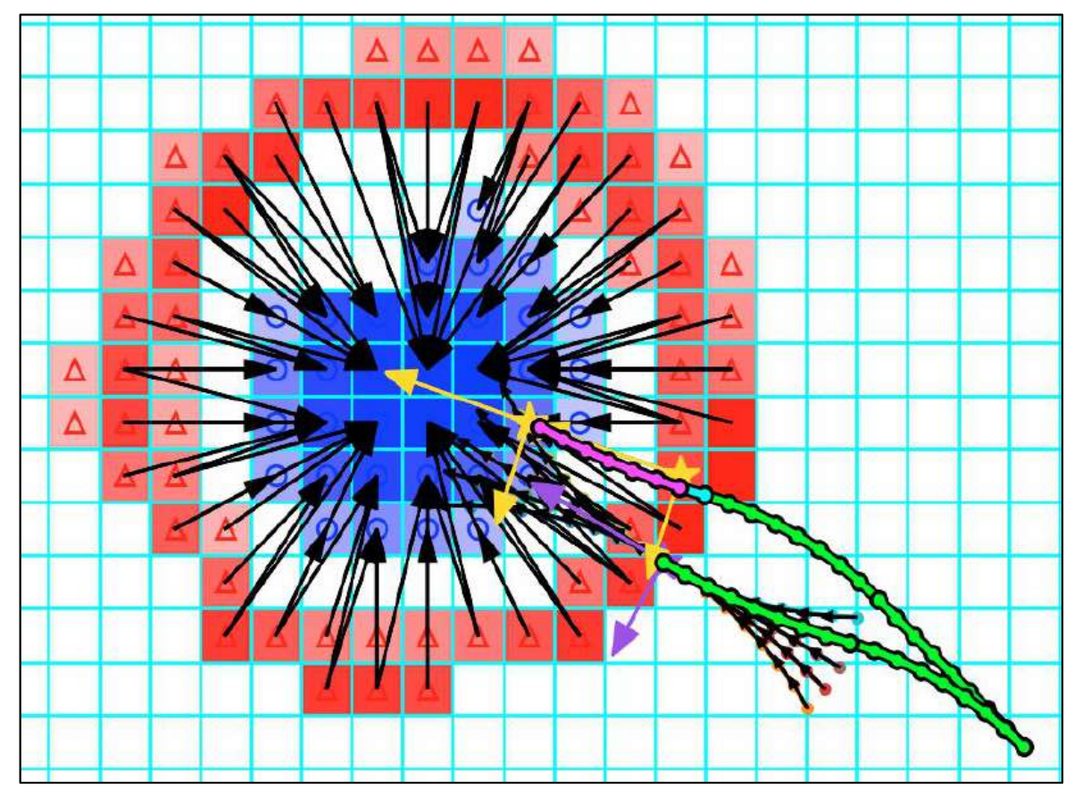
$$\min_{\Pi}\sum_{i,j}\Pi_{i,j}D_{i,j}$$

$$\begin{array}{c|c|cccc}
 & \text{Volume} & 0.4 & 0.1 & 0.3 & 0.2 \\
 & & x_1 & x_2 & x_3 & x_4 \\
\hline
y_1 & 0.3 & 0.3 & 0 & 0 & 0 \\
y_2 & 0.4 & 0.1 & 0.1 & 0.2 & 0 \\
y_3 & 0.3 & 0 & 0 & 0.1 & 0.2
\end{array} \; \Pi$$

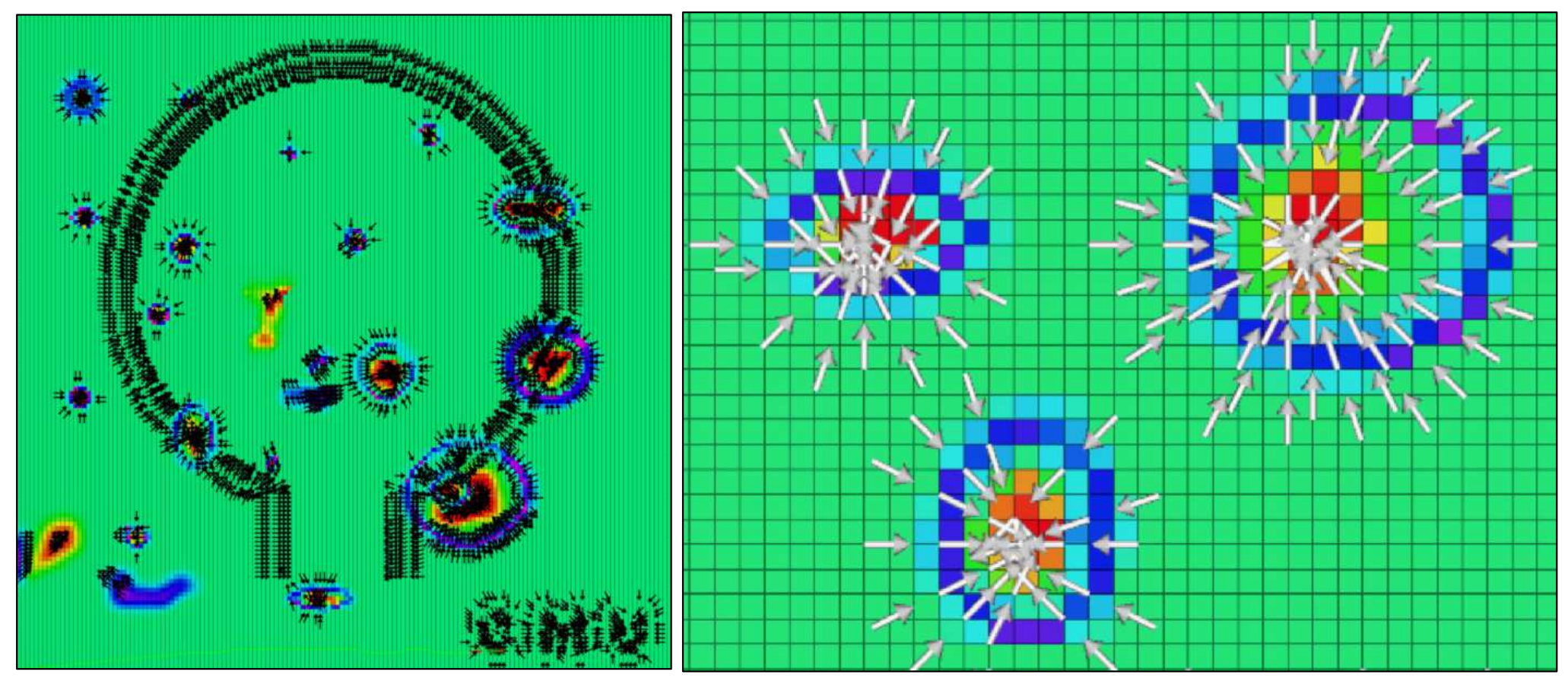
Transport Planner Optimization Formulation



Lattice-Based, Terrain-Aware Trajectory Planning



Crater Manipulation Planning and Trajectory



(a) Landing pad creation **(b)** Multiple craters

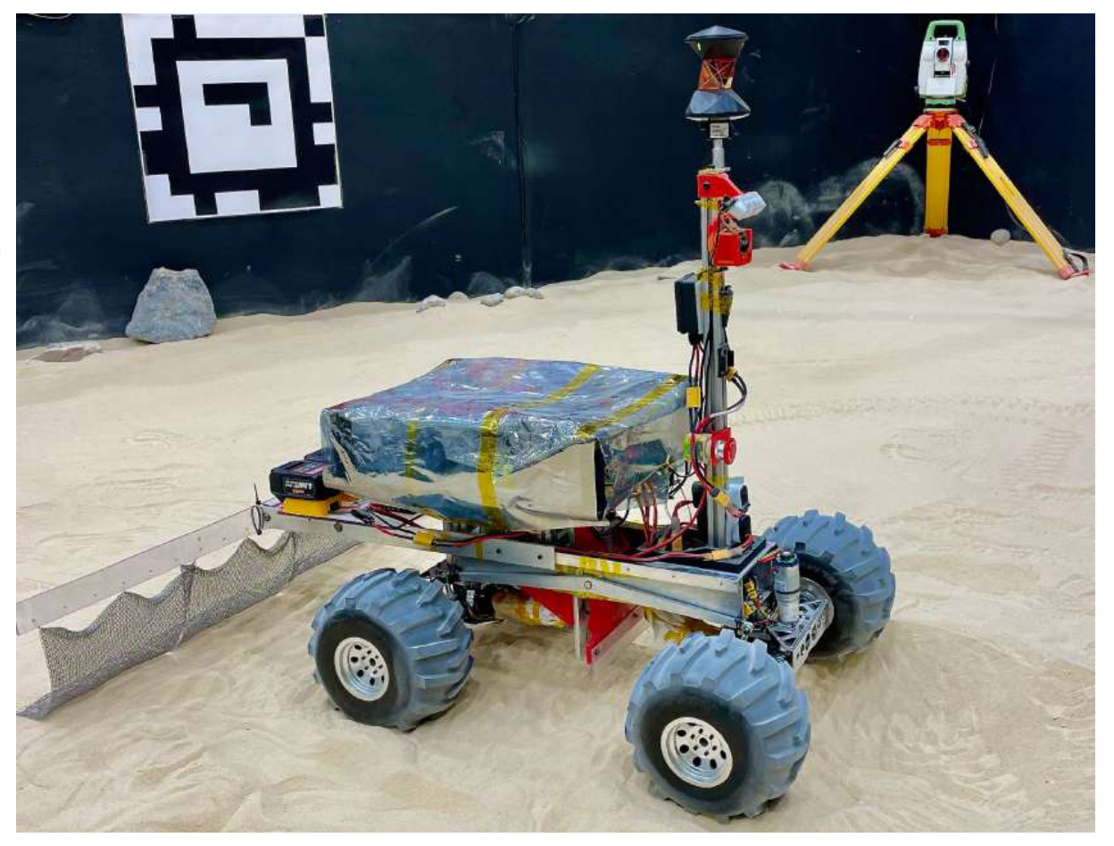
Example Transport Plans

Worksystem & Testing Infrastructure

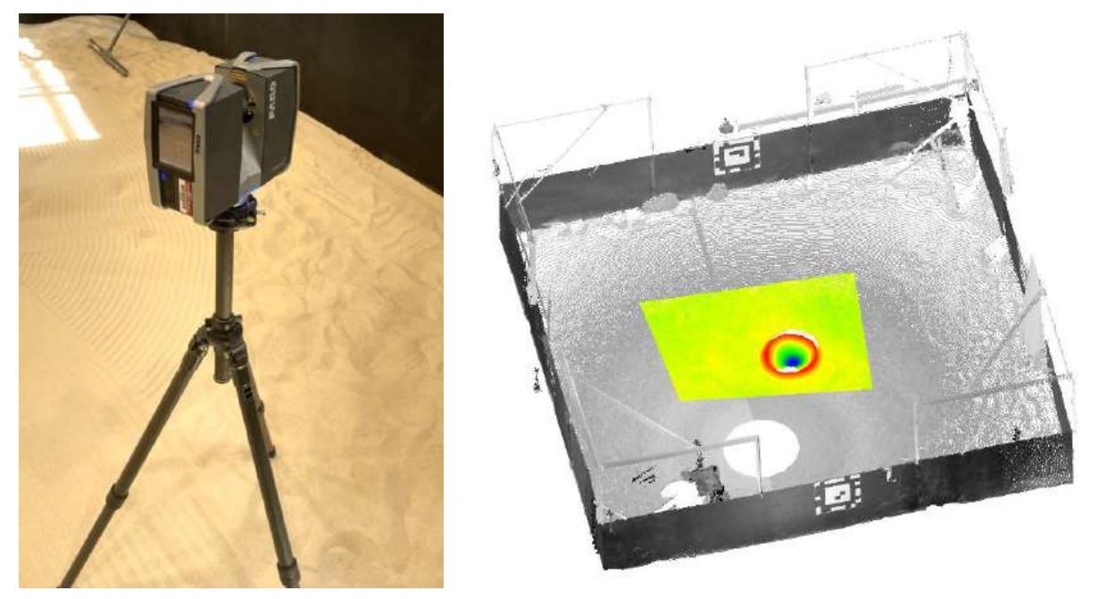
The CraterGrader worksystem is a flight-facing mobility, compute, sensing and tooling platform built to test software
- Capable worksystem with 4-wheel drive, double Ackermann steer, roll-averaging suspension
- Center-mounted tooling blade performs bulk of work, dozing and cutting regolith to level and smooth terrain
- Exploratory back-mounted stainless steel drag-mat removes high frequency height variations from the surface

Onboard Sensor Suite Measures and Localizes Terrain
- Vehicle odometry capturing drive, steer, and tool actuator positions
- Chassis-mounted IMU provides roll and pitch relative to local gravity normal
- An externally mounted robotic total station provides line-of-sight millimeter precision positioning to robot-mounted prism
- Sun sensor provides external reference for vehicle bearing
- Front-facing stereo camera provides point cloud information for close-range terrain

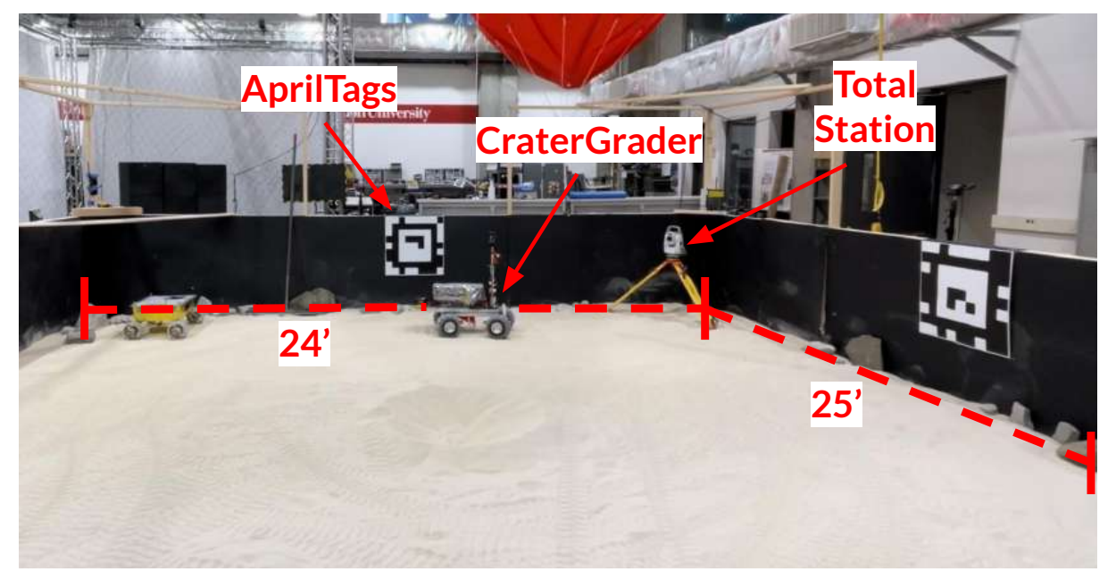
Test site in Carnegie Mellon University, Planetary Robotics Lab
- Indoor sandbox, ~ 50m^2
- Quikrete 1113 regolith simulant
- FARO 3D Laser Scanner for sub-millimeter topography ground truth



CraterGrader Worksystem



Laser Scan Topography Verification



MoonYard and Supporting Infrastructure

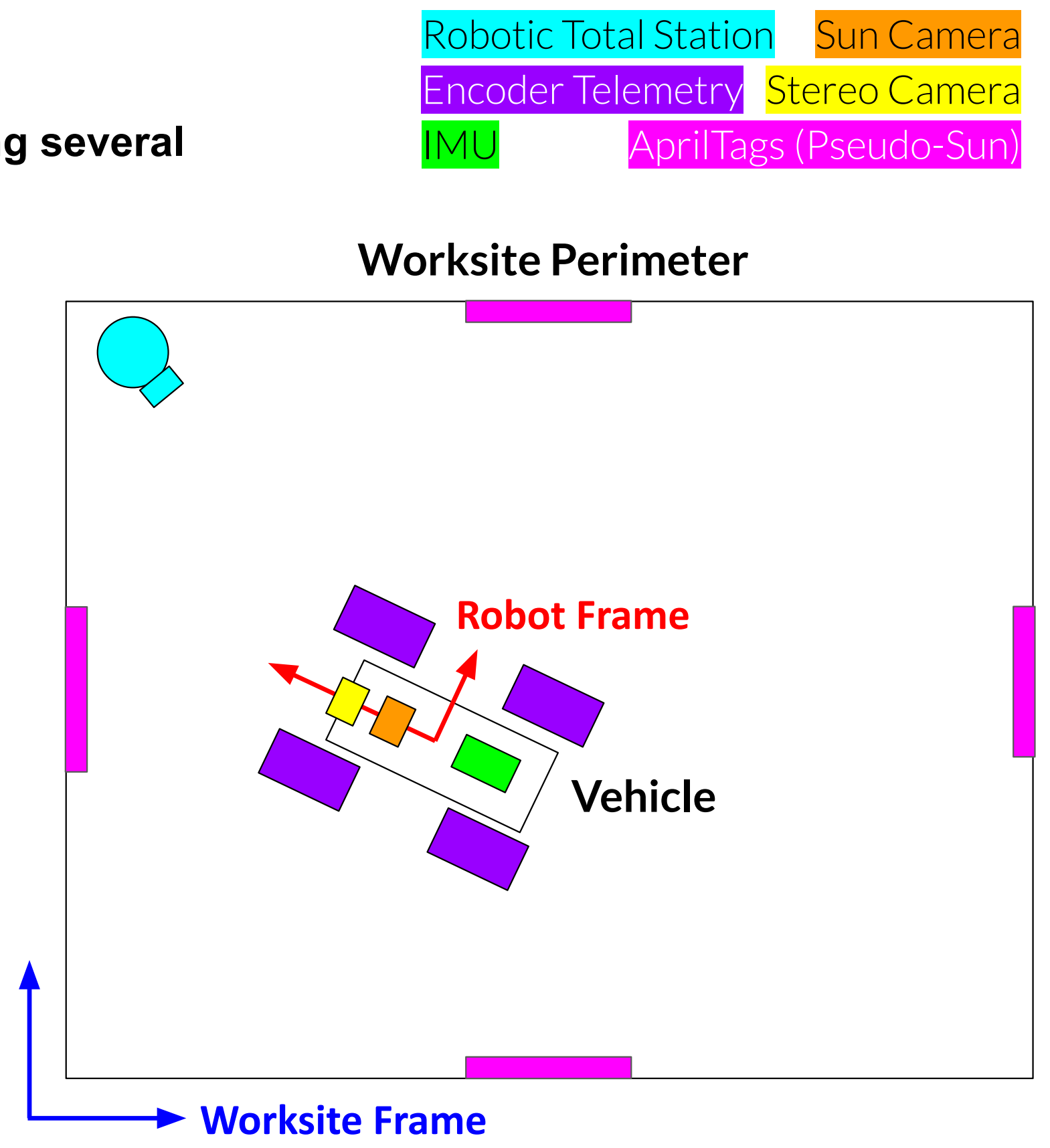
Localization & Control

The lunar surface presents unique challenges for localization unseen in terrestrial priors
- Operating in GPS-free environment
- Absence of magnetic field for bearing measurements
- Limited features in lunar surface, coupled with a changing map due to manipulation of terrain
- High dynamic range for most sensing modalities

$$\mathbf{x} = \begin{bmatrix} x \\ y \\ z \\ \theta \\ \phi \\ \psi \\ T \end{bmatrix} = \begin{bmatrix} ENCODER + IMU + TS \\ ENCODER + IMU + TS \\ ENCODER + IMU + TS \\ IMU + TS \\ IMU + TS \\ SUNSENSOR \\ ENCODERS \end{bmatrix}$$

Localization treated as a sensor fusion problem, using several sensing modalities:
- IMU
- Sun sensor (Stereo Camera)
  - Mimicked indoors using visual fiducial markers
- Tool, drive, and steer odometry
- Robotic total station, providing live position
- Strong slip-signal from difference between wheel velocity and global velocity estimate

Control couples steering, drive, and tool actuation:
- Stanley steering Controller
- Accounting for a slow steer response:
  - Trajectory heading look-ahead
  - Steering-based drive velocity penalty
- Low level velocity and position control



Sensor Suite for Localization

Results & Conclusions

Current Results

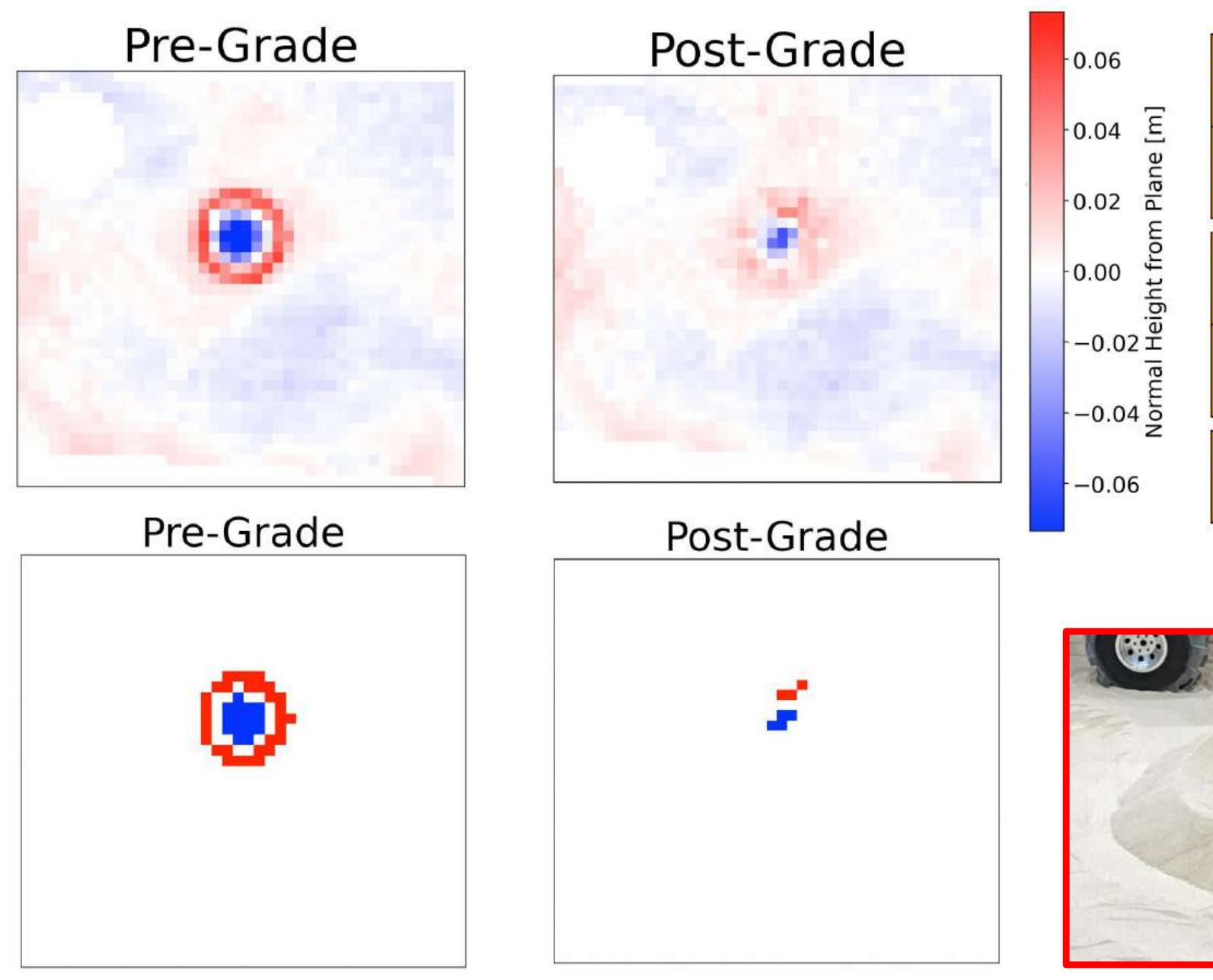
System engages full autonomy for end-to-end worksite grading
- Autonomous operation meets NASA proposed worksite specifications [1]: < 1° grade, < 1 cm RMS
- Self-imposed requirement for global max/min variation
- Average 1m diameter single crater **reduction in area out-of-spec of 88%** post-grade in just 30 minutes of runtime
- **Self imposed** +/- 3cm maximum deviation from fit plane not achieved but useful for tracking performance

Next Steps

Developing Cost Optimization Metrics
- Planners benchmarked by grading throughput and energetics

Improving State Representation
- Developing transition functions to predict terrain manipulation in the planning phase

Improving Slip and Blade Interaction for Control
- Closed loop slip to blade control useful for embedding protection and improving maximum carry



Laser Scan Verification of Worksite

	Initial		Final	Desired
Grade	0.12°	→	0.11°	±1°
Std Dev	1.25cm	→	0.7cm	1cm
Max Point	+7.6cm	→	+5.1cm	+3cm
Min Point	-12.3cm	→	-6.9cm	-3cm
Time	31 min 41 sec			

Average Performance Results over 4 Runs

Flattened Crater

[†] The Robotics Institute (https://www.ri.cmu.edu/), *Equal Contributors

[1] National Aeronautics and Space Administration, Space Technology Mission Directorate. SPACE TECHNOLOGY RESEARCH GRANTS PROGRAM, LUNAR SURFACE TECHNOLOGY RESEARCH OPPORTUNITIES APPENDIX, 2021.
[2] Y. Rubner, L. Guibas, and C. Tomasi, "The Earth Mover's Distance, Multi-Dimensional Scaling, and Color-Based Image Retrieval", Stanford, CA, 1997

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