National Aeronautics and Space Administration

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Multi-Objective and Multi-Scale Planning for Long-Range Planetary Rover Autonomy

Principal Investigator: Alberto Candela Garza (397);
Co-Investigators: Sriramya Bhamidipati (347), Tara Estlin (397),
David Wettergreen (Carnegie Mellon University), Abigail Breitfeld (Carnegie Mellon University)

Objectives: This work develops and validates onboard planning algorithms to enable robotic systems to consider multiple objectives while operating autonomously. We use Endurance as the mission use case, but our work is broadly applicable to autonomous rovers, spacecraft, and aerial vehicles. Our methods use a holistic understanding of the mission environment that includes science objectives, operation constraints, localization uncertainty, and navigation safety. We research multi-objective planning methods and evaluate them using real and relevant orbital of the Moon and Earth.

Background: The primary purpose of planetary explorers is to collect scientific information. Most decisions are made by humans balancing science goals with rover operations (power, communication, safety, etc.). Extensive ground-in-the-loop planning can become a bottleneck that reduces productivity (Gaines et al. 2017). There has been immense progress in rover autonomy to improve operations efficiency (Verma et al. 2023). Yet existing rover autonomy software cannot be directly repurposed for upcoming lunar missions. Lunar rovers will drive faster and farther at a tempo that precludes continuous ground guidance, with planning further complicated by dynamic illumination, temperature, and communication limits. Our work addresses these challenges for the Endurance mission concept: a ~2000 km traverse requiring a complex balance of science goals against constraints (Keane et al. 2021).

Approach and Results: The core of this work is a framework for adapting standard single-objective path planning algorithms, such as A*, for multi-objective tasks. We achieve this by using multi-objective decomposition, a technique that transforms a complex multi-objective problem into simpler, single-objective ones (Miettinen, 1998). We adapt four path planners to incorporate these decomposition methods: A*, MCTS, fixed-horizon search, and greedy search. Our approach compares three existing decomposition methods—Weighted Sum, Tchebychev, and Boundary Intersection (BI)—and introduces a novel method: a Euclidean Distance decomposition that finds the solution closest to an ideal "reference point" in the objective space (Fig. 1).

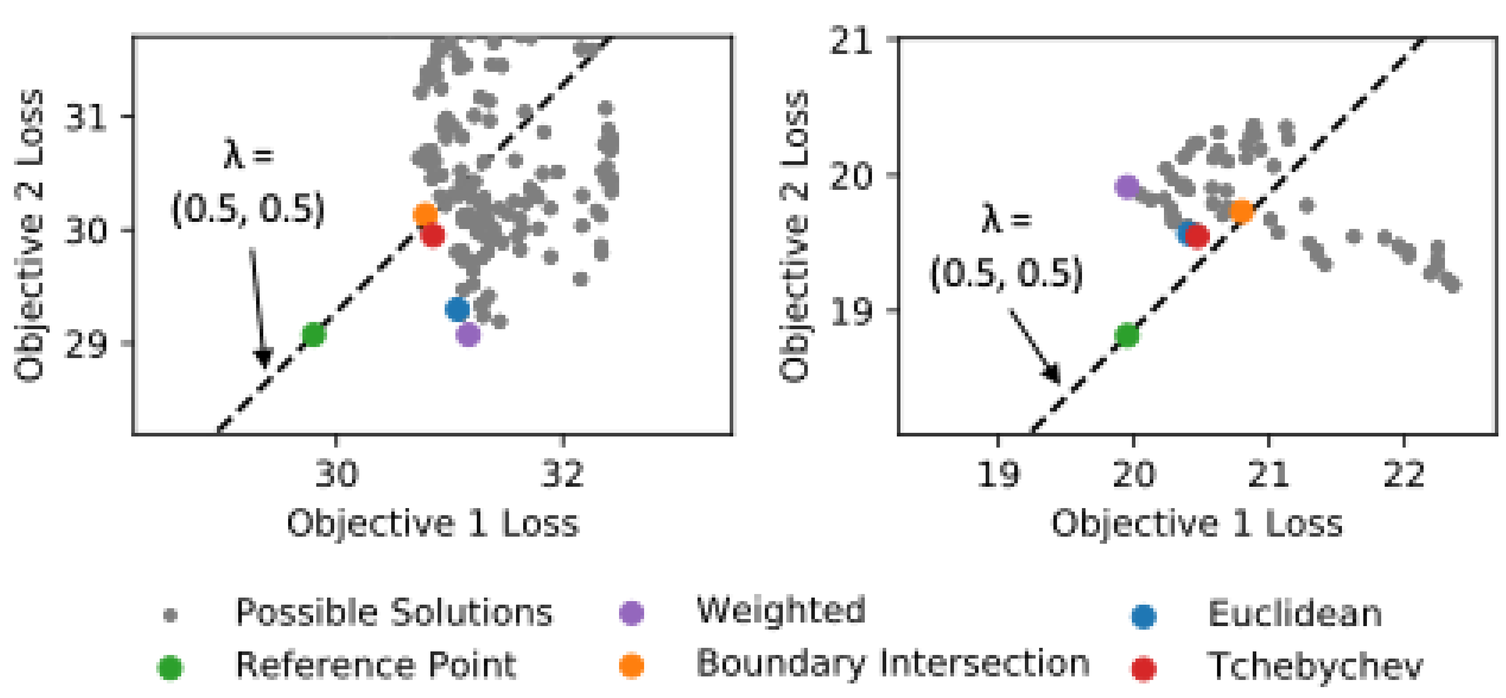

Fig. 1. Potential solutions for a path over two objectives. The weighted method of decomposition has varied and unpredictable behavior in objective space, while other methods are explainable and consistent.

We test the algorithms in simulations using two realistic rover exploration scenarios and real-world data (Fig 2). For the Lunar Rover Scenario, which is based on the Endurance mission concept (Keane et al. 2021), the rover must balance four objectives: scientific interest, lighting conditions, safety, and "keep out" regions; we use data from the USGS Unified Geologic Map of the Moon (Fortezzo et al. 2020) and LOLA elevation models (Barker et al. 2016). The Terrestrial Rover Scenario involves a rover exploring a geologically significant area in Cuprite, NV and balancing three objectives: scientific interest (based on an evolving entropy map from Candela et al. 2020), lighting conditions, and safety.

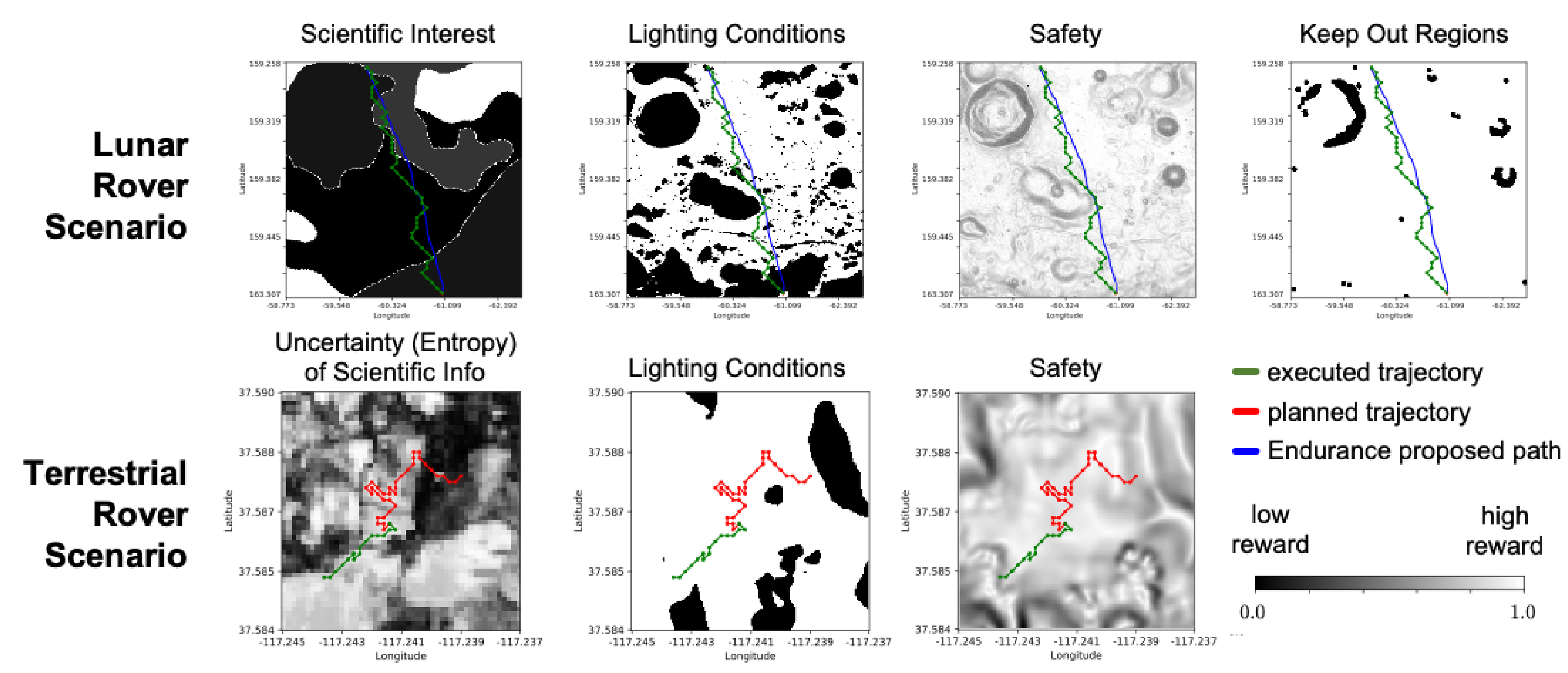

Fig. 2. Objective maps and example planned paths using the boundary intersection A method for the lunar and terrestrial rover scenarios.*

Our experiments demonstrate that the proposed explainable methods achieve equivalent or improved solution quality compared to the baselines (Fig. 3). The main advantage is explainability without sacrificing performance. These methods produce predictable actions and adhere more closely to the desired trade-off between objectives.

Lunar Rover Scenario

Planning Method	Decomp. Method	Average % Interest Reduction ↑	Average in Sun % ↑	Average Safety % ↑	Average Keep In % ↑	Solution Quality (TOPSIS) ↑	P-value	Distance to λ ↓
A*	EUCLID	78.765	89.551	92.186	99.683	0.869 ± 0.049	1.000	18.839
	BI	78.765	89.579	92.135	99.683	0.869 ± 0.049	0.593	18.819
	TCHEBYCHEV	**78.842**	89.577	**92.452**	99.683	**0.870** ± 0.049	0.893	18.826
	WEIGHTED	78.765	**89.650**	92.096	99.683	0.869 ± 0.049	-------	**18.728**
MCTS	EUCLID	**78.129**	**82.540**	90.225	97.369	**0.841** ± 0.046	0.075	**20.362**
	BI	77.910	82.352	90.210	97.075	0.840 ± 0.047	0.249	20.420
	TCHEBYCHEV	77.300	80.553	89.531	**97.490**	0.832 ± 0.048	0.612	21.699
	WEIGHTED	77.480	82.217	**90.341**	97.369	0.838 ± 0.048	-------	21.032
FIXED HORIZON	EUCLID	75.110	81.178	90.441	97.527	0.827 ± 0.061	0.715	23.730
	BI	75.040	**81.316**	**90.658**	**97.725**	0.828 ± 0.061	0.655	23.957
	TCHEBYCHEV	**76.504**	81.095	89.900	97.413	**0.832** ± 0.056	0.345	**22.153**
	WEIGHTED	75.046	80.275	90.654	**97.725**	0.824 ± 0.059	-------	24.717
GREEDY	EUCLID	75.567	75.148	90.204	97.982	0.808 ± 0.056	-------	27.386
	BI	75.567	75.148	90.204	97.982	0.808 ± 0.056	-------	27.386
	TCHEBYCHEV	75.567	75.148	90.204	97.982	0.808 ± 0.056	-------	27.386
	WEIGHTED	75.567	75.148	90.204	97.982	0.808 ± 0.056	-------	27.386
ENDURANCE PATH		75.074	78.828	91.673	98.457	0.820 ± 0.056	-------	26.219
RANDOM		76.147	73.041	88.406	96.38	0.804 ± 0.060	-------	24.974

Terrestrial Rover Scenario

Planning Method	Decomp. Method	Average % Entropy Reduction ↑	Average in Sun % ↑	Average Safety % ↑	Solution Quality (TOPSIS) ↑	P-value	Distance to λ ↓
A*	EUCLID	**71.014**	98.800	86.669	**0.823** ± 0.024	0.862	19.979
	BI	71.013	98.760	86.636	**0.823** ± 0.024	0.761	19.930
	TCHEBYCHEV	70.230	97.280	85.264	0.814 ± 0.024	0.010	**19.484**
	WEIGHTED	70.760	**98.936**	**86.683**	0.822 ± 0.023	-------	20.244
MCTS	EUCLID	**67.388**	**97.832**	**83.793**	**0.798** ± 0.033	**0.004**	22.027
	BI	67.341	97.072	83.030	0.795 ± 0.029	0.083	21.507
	TCHEBYCHEV	67.333	96.304	82.568	0.793 ± 0.034	0.332	**21.070**
	WEIGHTED	65.946	97.776	83.063	0.789 ± 0.034	-------	23.163
FIXED HORIZON	EUCLID	**68.062**	96.584	**84.638**	**0.801** ± 0.032	**0.030**	**20.780**
	BI	67.569	96.312	84.430	0.798 ± 0.034	0.351	20.997
	TCHEBYCHEV	67.684	**96.624**	84.170	0.798 ± 0.029	0.265	21.059
	WEIGHTED	67.385	96.432	84.127	0.796 ± 0.035	-------	21.191
GREEDY	EUCLID	**67.777**	96.096	83.959	**0.797** ± 0.036	0.632	**20.572**
	BI	67.561	**96.152**	**84.058**	**0.797** ± 0.035	0.664	20.752
	TCHEBYCHEV	66.947	95.904	83.707	0.793 ± 0.036	0.147	21.125
	WEIGHTED	67.708	95.720	83.914	0.795 ± 0.039	-------	20.808

Fig. 3. Results for lunar and terrestrial rover scenarios.

Significance/Benefits to JPL and NASA: Long-distance autonomous driving technology is critical for upcoming lunar missions, including Endurance and Artemis activities using Lunar Terrain Vehicles (LTVs). This technology is essential for achieving mission goals while reducing operational costs by enabling longer autonomous drives and decreasing the need for frequent ground contact. Beyond the Moon, this work benefits future Mars missions, such as the Mars Science Helicopter and robotic elements of a human campaign. It is also applicable to any in-situ spacecraft designed for autonomous travel over significant distances to destinations like Titan, Europa, or Venus.

References:

- M. K. Barker et al., "A New Lunar Digital Elevation Model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera," Icarus, 2016.
- A. Candela et al., "Planetary Rover Exploration Combining Remote and In Situ Measurements for Active Spectroscopic Mapping," IEEE ICRA, 2020.
- C. Fortezzo et al., "Release of the Digital Unified Global Geologic Map of the Moon at 1:5,000,000-Scale," LPSC. Lunar and Planetary Institute, 2020.
- D. Gaines et al., "A Case Study of Productivity Challenges in Mars Science Laboratory Operations," International Workshop on Planning and Scheduling for Space, 2017.
- J. T. Keane et al., "Endurance: Lunar South Pole-Aitken Basin Traverse and Sample Return Rover," Mission Concept Study for the 2023-2032 Planetary Science and Astrobiology Decadal Survey, 2021.
- K. Miettinen, Nonlinear Multiobjective Optimization (International Series in Operations Research & Management Science), 1998.
- V. Verma et al., "Autonomous Robotics Is Driving Perseverance Rover's Progress on Mars," Science Robotics 8, 2023.

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Publications:

A. Breitfeld, A. Candela, S. Bhamidipati, T. Estlin, D. Wettergreen, "Multi-Objective Graph-Based Path Planning Using Decomposition Approaches for Exploration Rovers," submitted to *IEEE International Conference on Robotics and Automation (ICRA)*, Vienna, Austria, 2026.

PI/Task Mgr. Contact Information:

alberto.candela.garza@jpl.nasa.gov 626-689-5104