Constraint-aware motion planning for vehicles with terrain traversability assessment and optimization in construction scenarios

Chenlong Feng[1], Jixin Wang[1], Qi Wang[3], Yuying Shen*[2], Xinxing Liu[1], Quan Zhang[4], Hongyu Ren[1], Yi Xiong[5]

1. Jilin University, 2. Southwest Jiaotong University

3. Zhejiang University, 4. Harbin Institute of Technology

5. Hangzhou Institute for Advanced Study, UCAS

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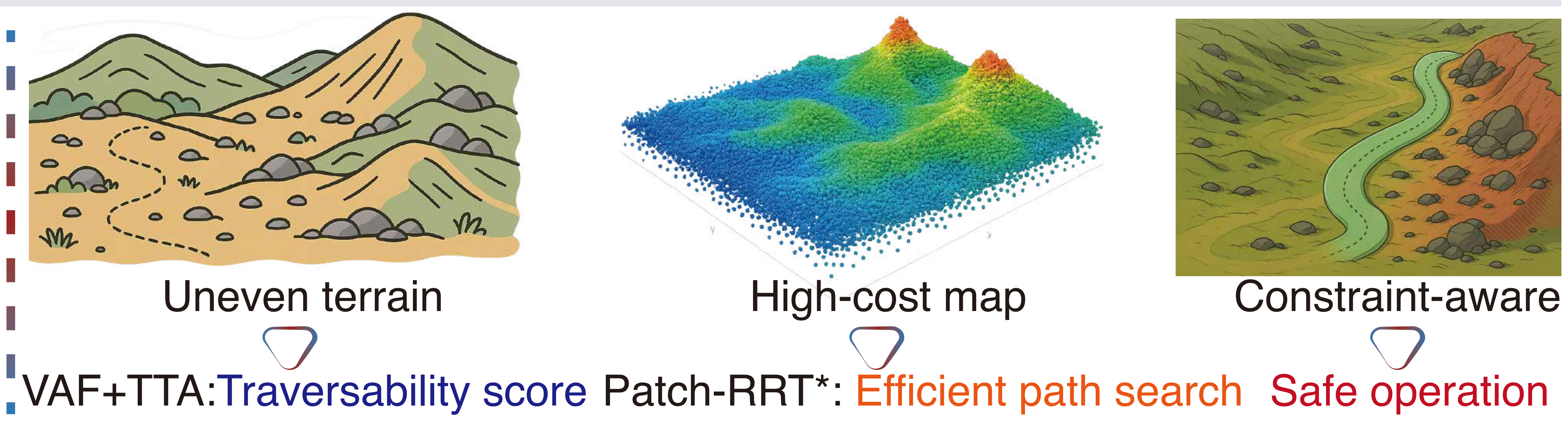
Abstract

Autonomous wheeled vehicles in construction must plan motions through uneven, cluttered terrain. We propose **a constraint-aware planning method with terrain traversability assessment (TTA) that unifies vehicle dynamics and terrain geometry into a continuous cost.** A terrain-aware Patch-RRT* rapidly finds feasible paths, which define safety constraints. We then optimize trajectories with Bézier curves under safety, waypoint, continuity, and dynamic constraints while modeling vehicle–terrain coupling. Simulation and real-world tests show **smoother paths, improved stability, and higher planning efficiency versus traditional planners.** The approach offers a practical solution for reliable motion planning in complex construction scenarios.

Motivation and Contributions

- Terrain–vehicle coupling makes feasibility hard on uneven terrain.
  —TTA+VAF fuse geometry & dynamics to yield continuous costs.
- Full-map search is slow and random sampling often ignores terrain.
  —Patch-RRT* evaluates terrain on demand and speeds safe paths.
- Complex terrain demands constraint-aware trajectory optimization.
  —Bézier optimization enforces terrain-aware safety and dynamics.



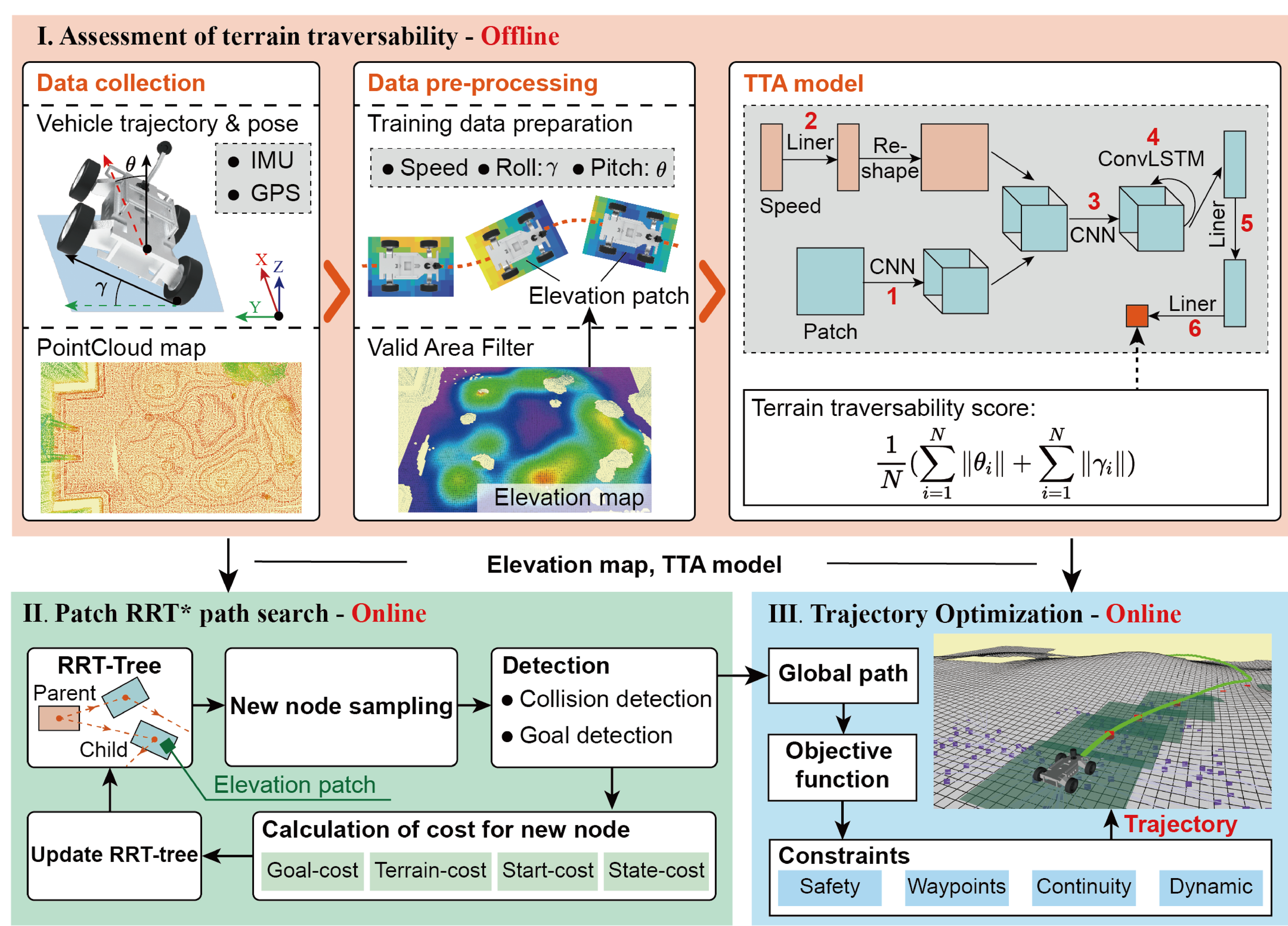
Methods

- **Terrain traversability.** Collect IMU/GPS/LiDAR and build PointCloud via A-LOAM. Apply VAF to keep traversable points and convert to indexable elevation map. Extract trajectory-aligned elevation patches, assign pose-dependent scores, train TTA model that fuses terrain geometry with vehicle dynamics.

$$\left|\arctan\left(\frac{p_z - p_z^{\mathrm{D}}}{\sqrt{(p_x - p_x^{\mathrm{D}})^2 + (p_y - p_y^{\mathrm{D}})^2}}\right)\right| \le \alpha$$

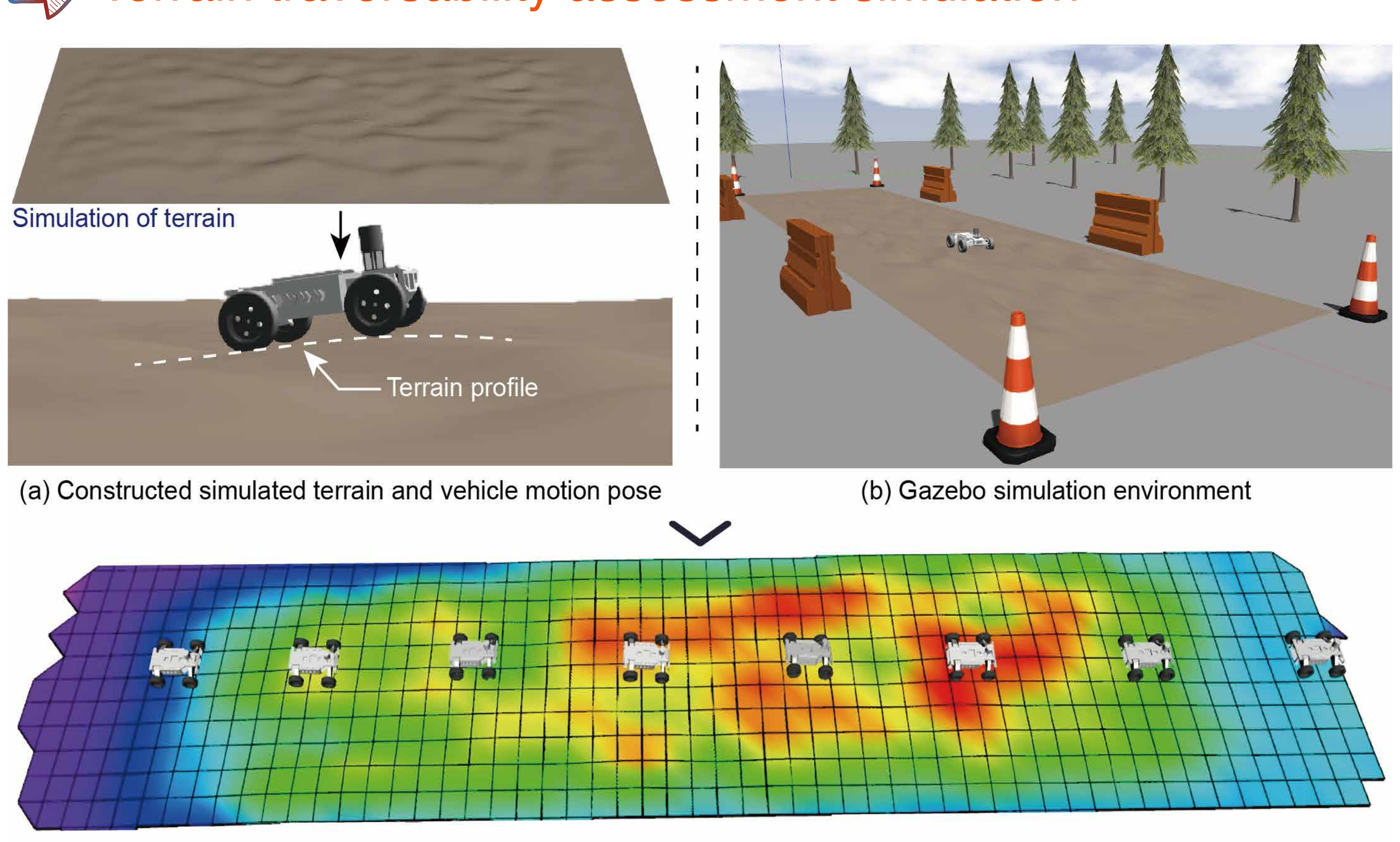
- **Patch-RRT* path search.** Reconstructs RRT node/edge representation and introduces a terrain-traversability cost, evaluating terrain on demand over elevation patches to guide sampling and rewiring for efficient, safe path search.
- **Constraint-aware trajectory optimization.** Represent the trajectory as piecewise Bézier. Build a safety corridor from the Patch-RRT* path; enforce waypoint, continuity, and dynamic feasibility via Bernstein derivatives. Minimize jerk plus traversability cost to yield smooth, safe, executable motion.

$$\min_{\boldsymbol{c}_x,\boldsymbol{c}_y,\boldsymbol{T}} \int_0^{T^a} \left(\mathbf{j}(t)^\top \mathbf{j}(t) + \rho_{ter} \cdot \mathcal{L}(f_x(t), f_y(t))\right) \mathrm{d}t + \boldsymbol{\rho}_T^\top \boldsymbol{T}$$



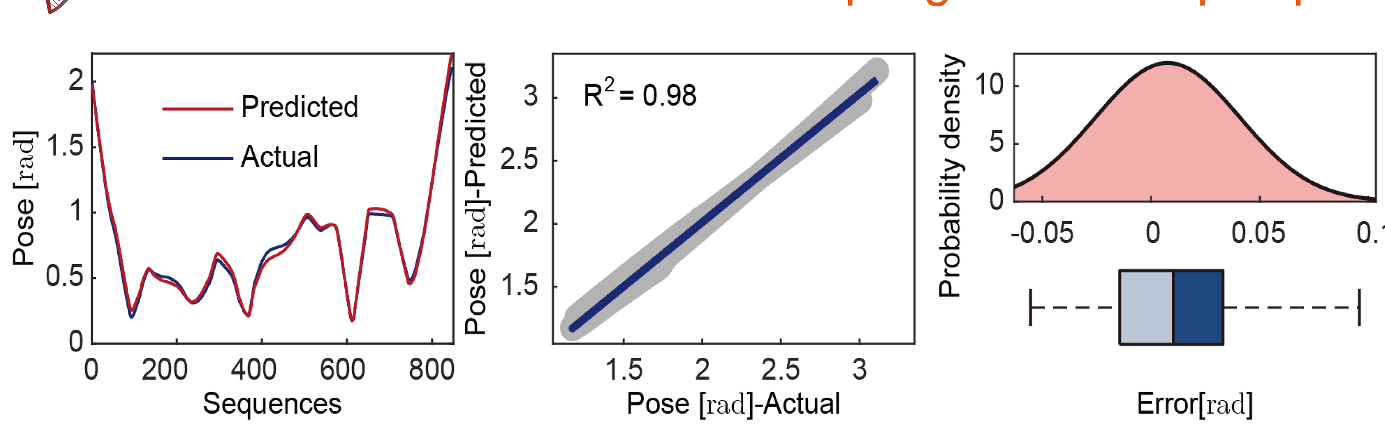
Experiments

Terrain traversability assessment simulation



(a) Constructed simulated terrain and vehicle motion pose
(b) Gazebo simulation environment
(c) Elevation map and vehicle trajectory

Verification of vehicle-terrain coupling relationship capture

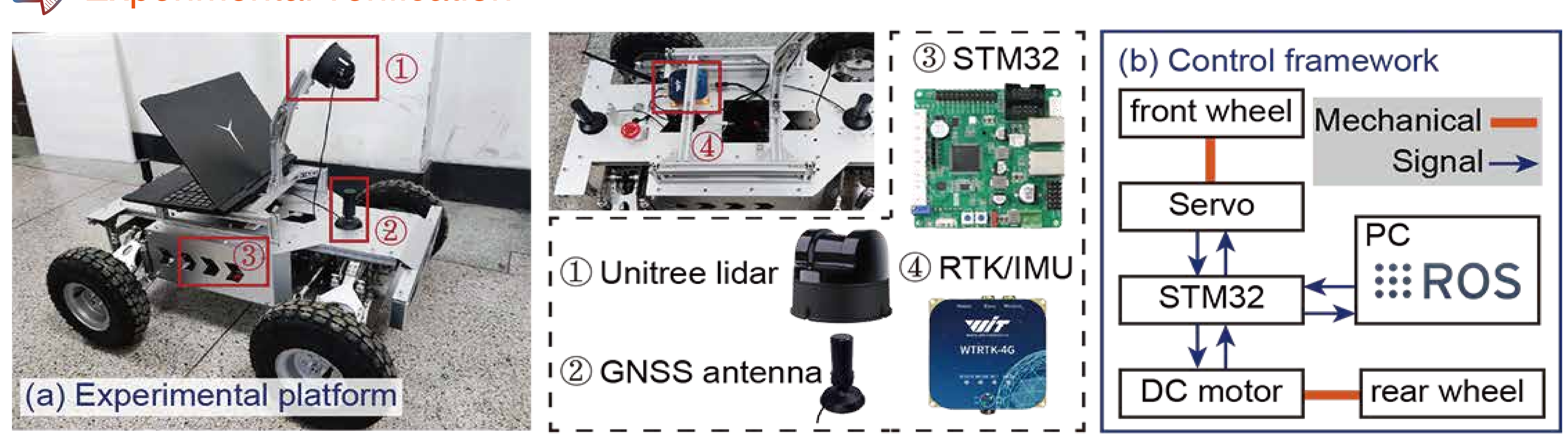


(a) Predictive results
(b) Predictive accuracy
(c) Predictive error

Table: Validation of interaction of TTA with vehicle dynamics.

Type	No-speed networks			TTA model		
	MAE	RMSE	R^2	MAE	RMSE	R^2
0.5 m/s	3.677	4.574	0.859	0.805	1.167	0.976
1.0 m/s	4.430	5.389	0.696	1.558	2.005	0.966
1.5 m/s	5.475	6.869	0.620	1.798	2.222	0.960
2.0 m/s	8.292	10.846	0.533	2.405	2.986	0.965
3.0 m/s	11.243	15.591	0.396	2.499	2.980	0.972

Experimental verification



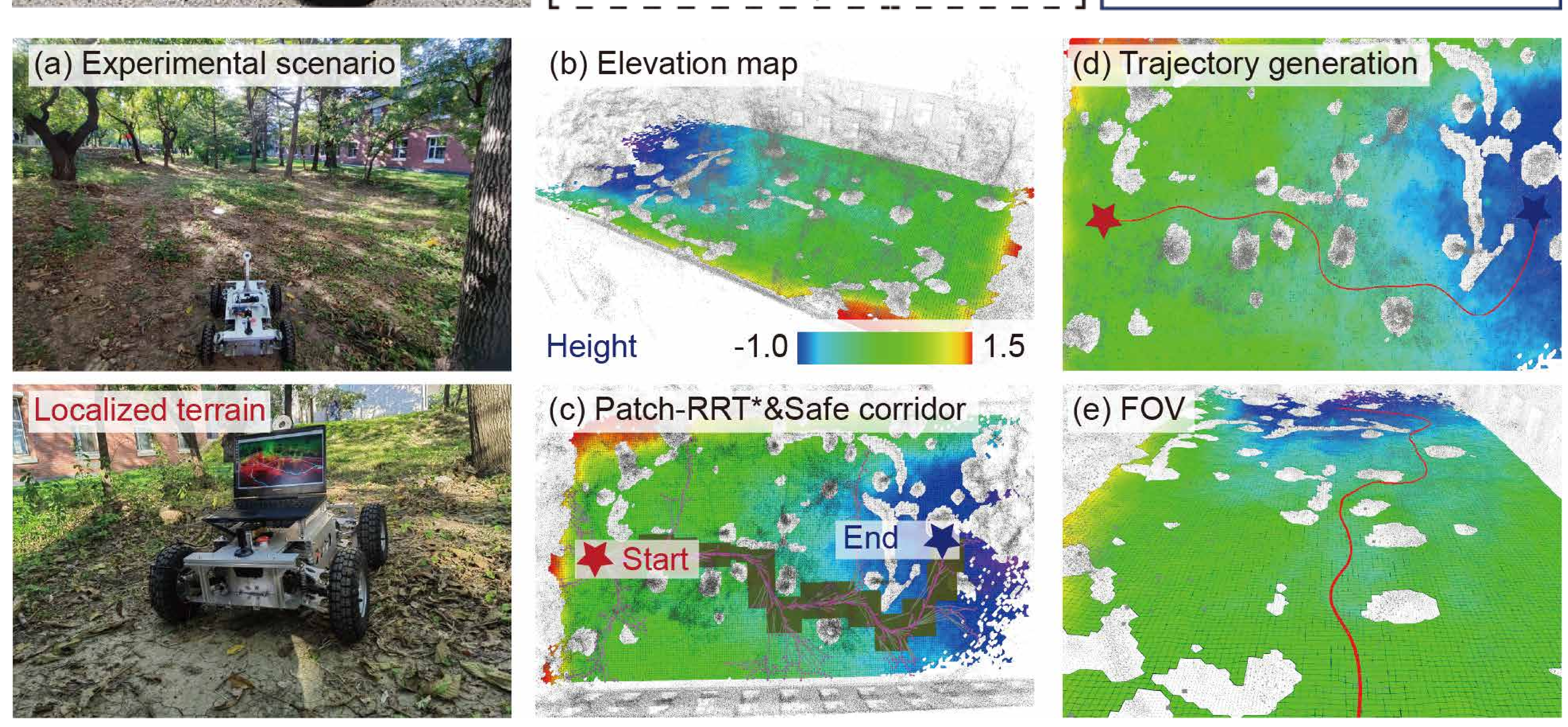


Table: Performance comparison of different motion planning methods.

Type	Trajectory time (s)	Trajectory length (m)	Average speed (m/s)	Average acc (m/s^2)	Maximum absolute pose (deg)	Average absolute pose (deg)	Time cost (ms)
RSPMP	18.876	37.091	0.983	0.345	13.517	6.593	-
T-Hybrid A*	17.042	35.762	0.825	0.392	19.462	7.188	32.487
PUTN-RRT*	14.012	32.367	0.851	0.374	14.484	6.7978	35.947
A*-RRT-LTR	12.987	30.635	0.834	0.405	15.028	5.8304	30.273
Proposed	**10.028**	**24.248**	**1.023**	**0.274**	**10.430**	**4.029**	**25.634**

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Contact: Chenlong Feng, Jilin University, fengcl24@mails.jlu.edu.cn

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