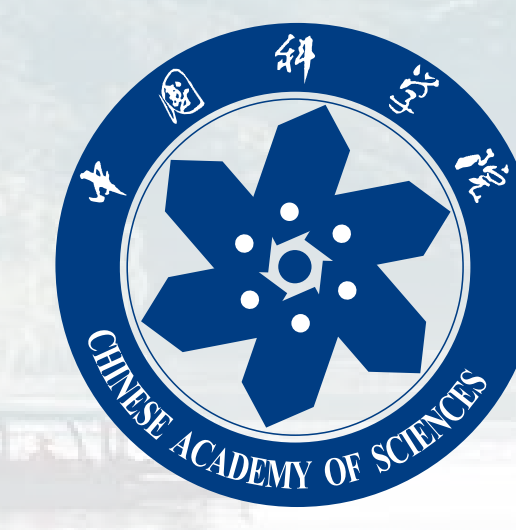


Constraint-aware motion planning for vehicles with terrain traversability assessment and optimization in construction scenarios

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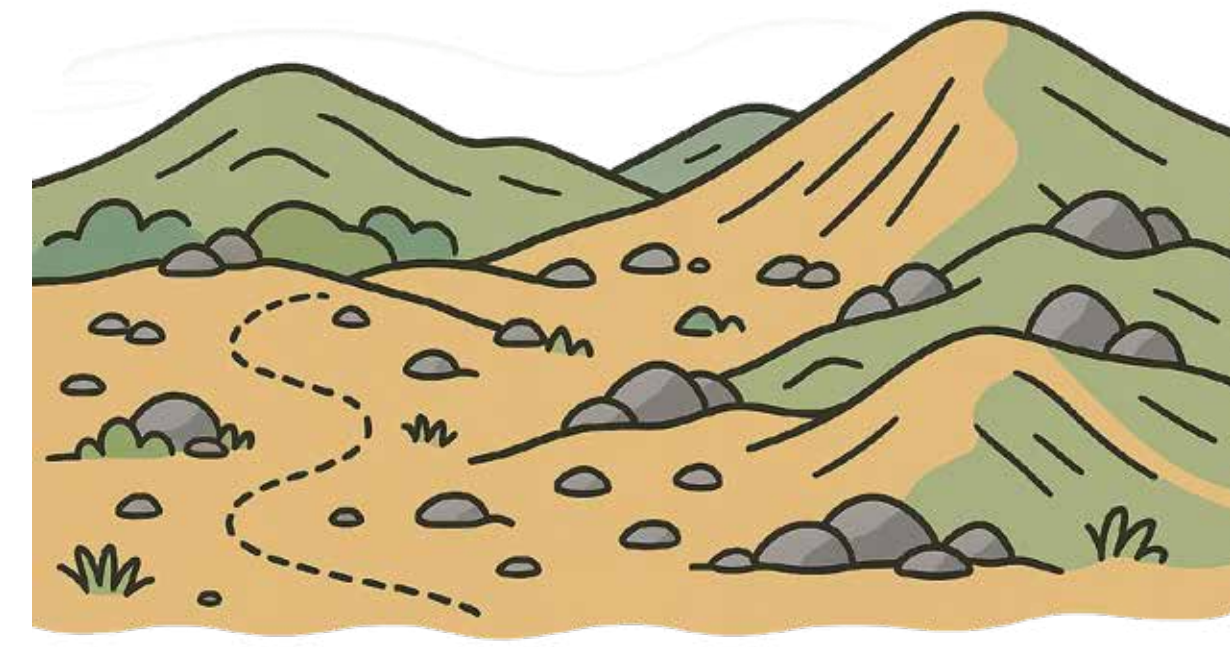


Abstract

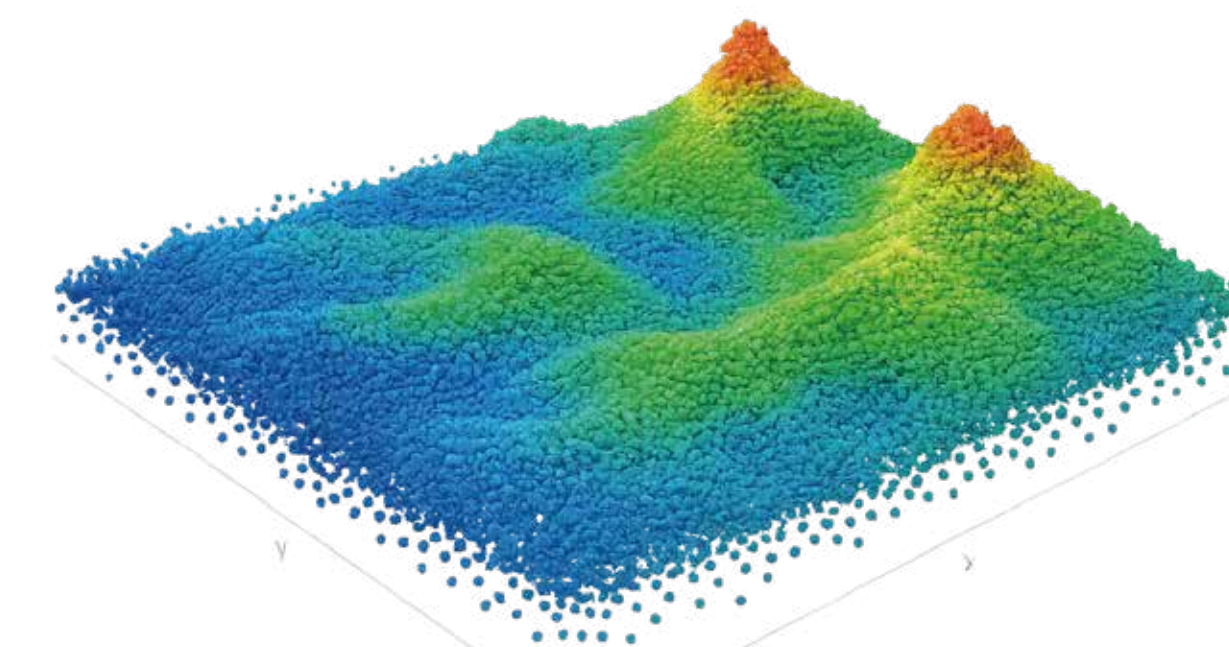
Autonomous wheeled vehicles in construction must plan motions through uneven, cluttered terrain. We propose a **constraint-aware planning method with terrain traversability assessment (TTA)** that unifies vehicle dynamics and terrain geometry into a continuous cost. A terrain-aware Patch-RRT* rapidly 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.



Uneven terrain



High-cost map



Constraint-aware

VAF+TTA: Traversability score Patch-RRT*: Efficient path search Safe operation

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.

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

- ➡ **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.

$$\min_{c_x, c_y, T} \int_0^{T^a} (\mathbf{j}(t)^T \mathbf{j}(t) + \rho_{ter} \cdot \mathcal{L}(f_x(t), f_y(t))) dt + \rho_T^T T$$

I. Assessment of terrain traversability - Offline

Data collection

Vehicle trajectory & pose

- IMU
- GPS

PointCloud map

Elevation patch

Valid Area Filter

Elevation map

Data pre-processing

Training data preparation

- Speed
- Roll: γ
- Pitch: θ

Elevation patch

Valid Area Filter

Elevation map

TTA model

Speed

Re-shape

ConvLSTM

CNN

Liner

Liner

Terrain traversability score:

$$\frac{1}{N} \left(\sum_{i=1}^N \|\theta_i\| + \sum_{i=1}^N \|\gamma_i\| \right)$$

II. Patch RRT* path search - Online

RRT-Tree

Parent

Child

New node sampling

Detection

- Collision detection
- Goal detection

Update RRT-tree

Calculation of cost for new node

Goal-cost

Terrain-cost

Start-cost

State-cost

III. Trajectory Optimization - Online

Global path

Objective function

Constraints

Safety

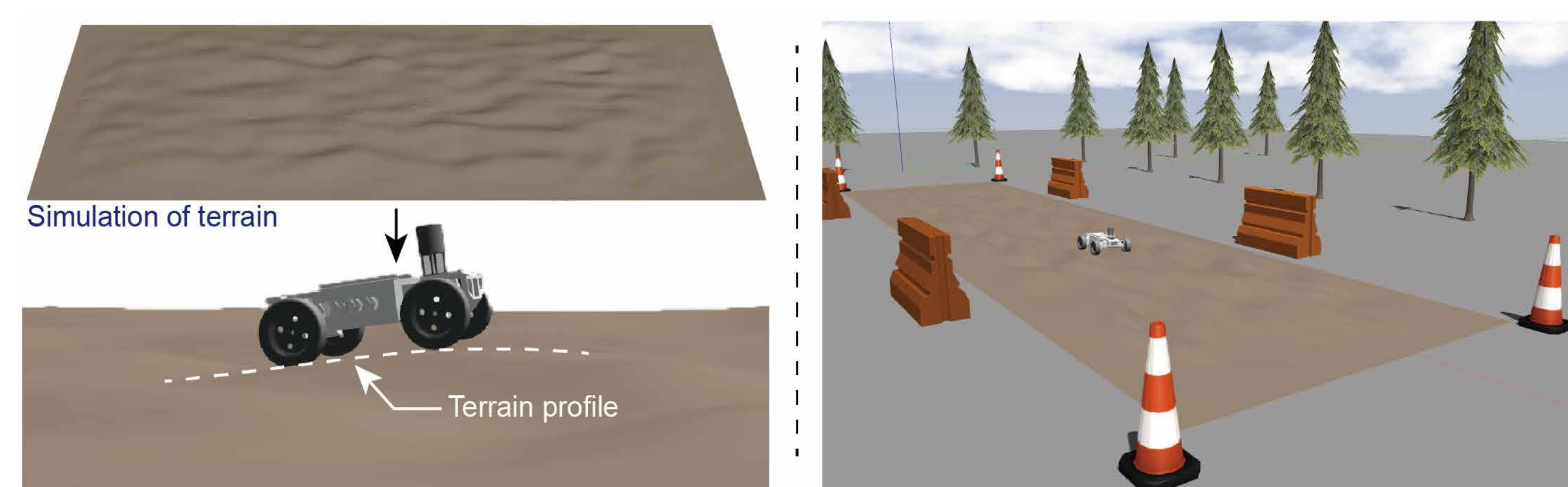
Waypoints

Continuity

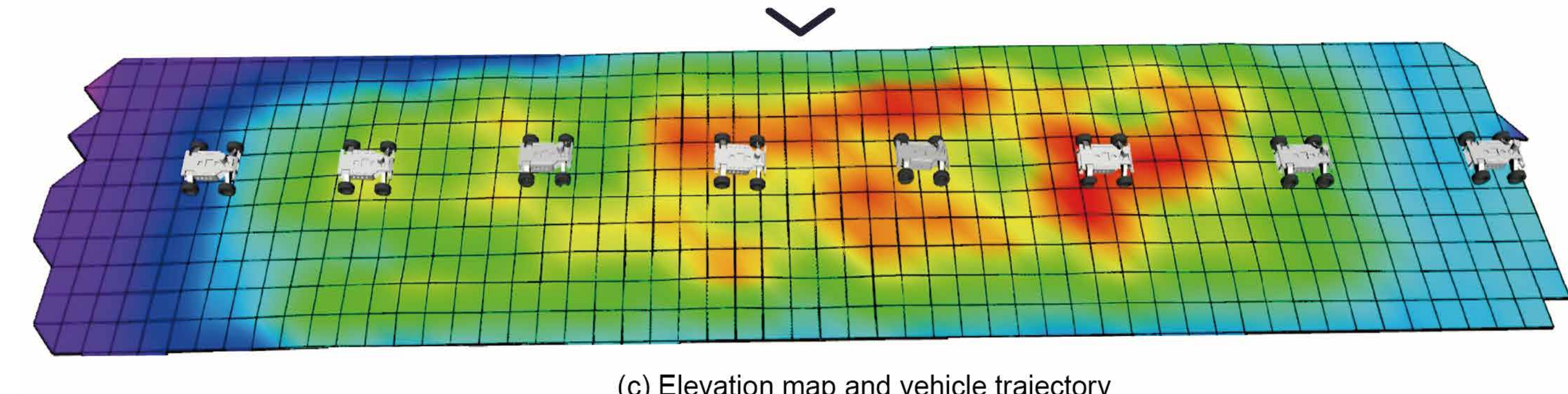
Dynamic

Experiments

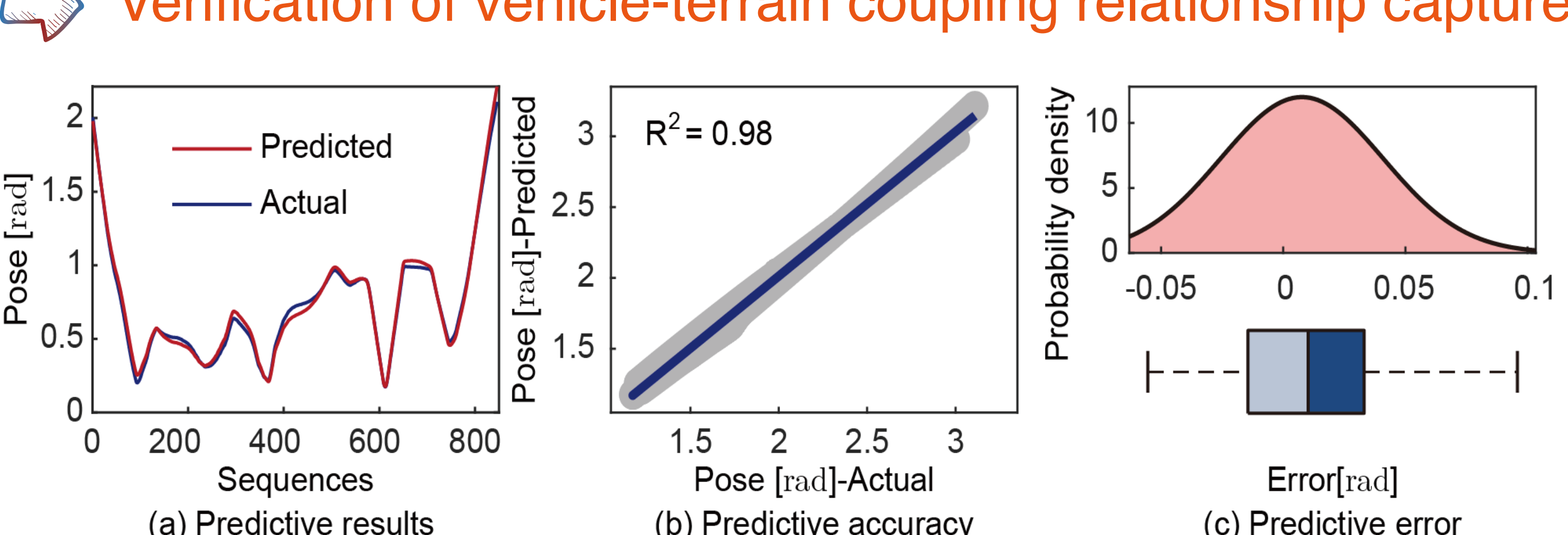
Terrain traversability assessment simulation



(a) Constructed simulated terrain and vehicle motion pose



(b) Gazebo simulation environment



Verification of vehicle-terrain coupling relationship capture

Predicted vs Actual

$R^2 = 0.98$

Probability density

Error [rad]

(a) Predictive results

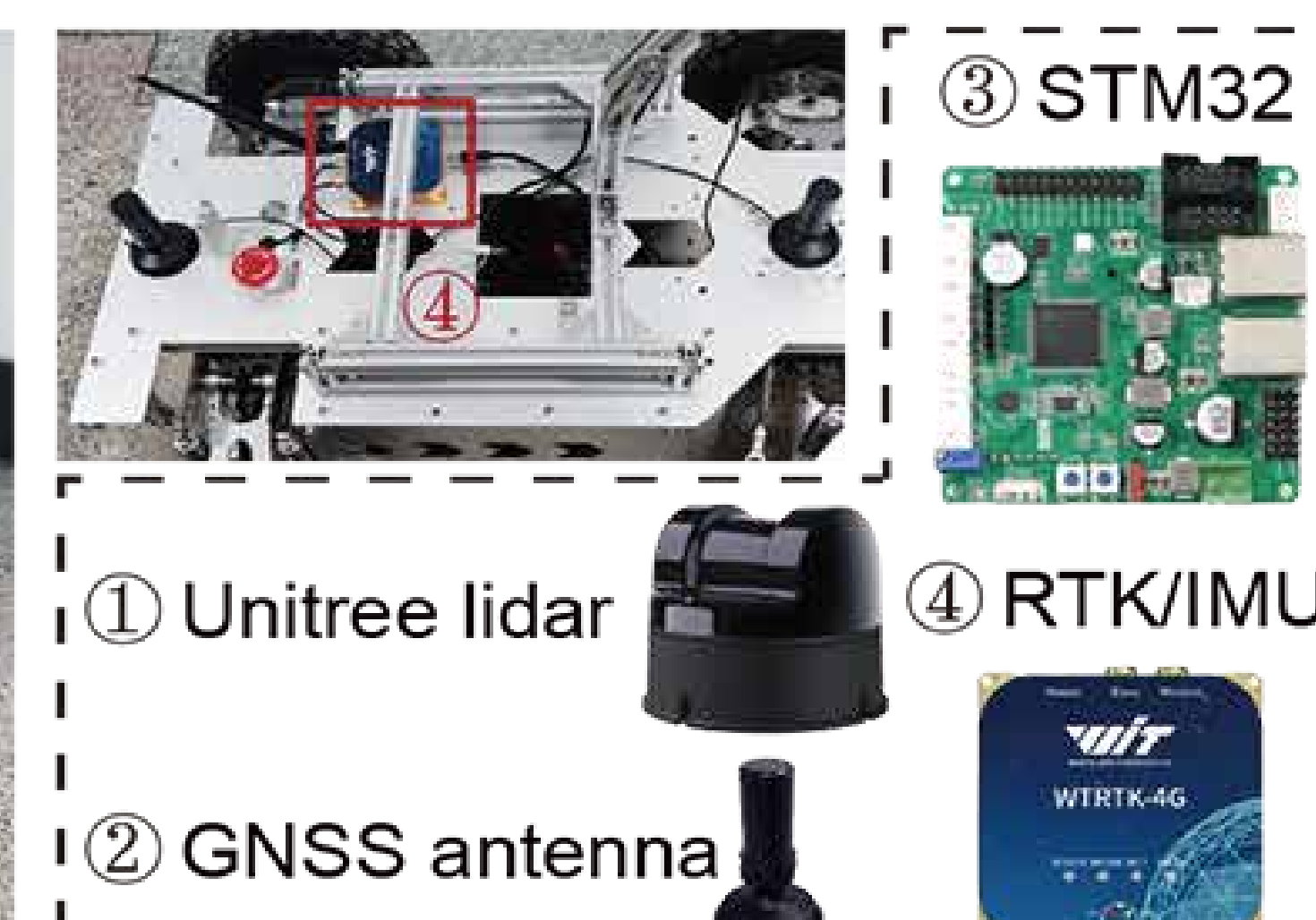
(b) Predictive accuracy

(c) Predictive error

Experimental verification



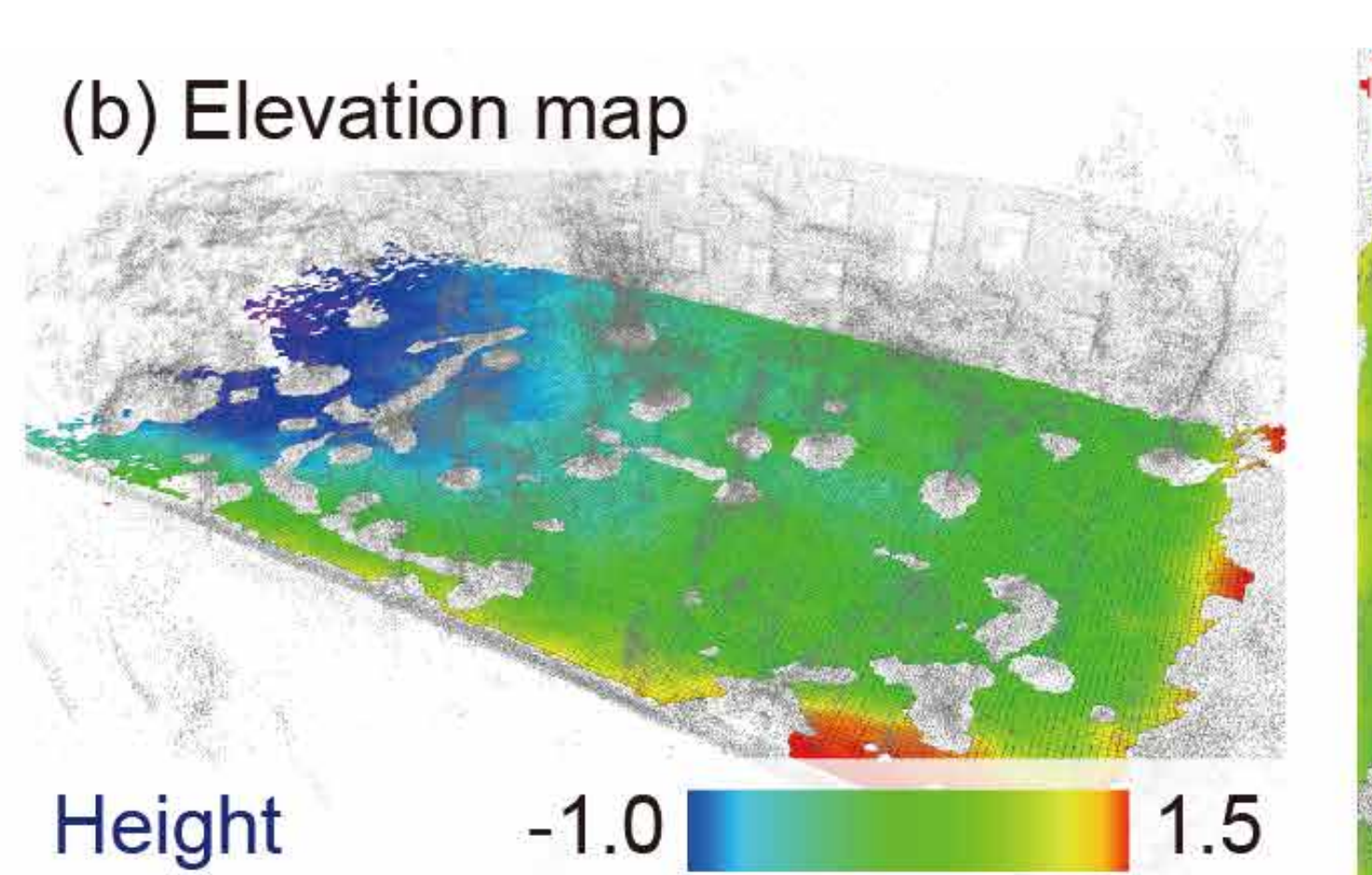
(a) Experimental platform



(b) Control framework



(a) Experimental scenario



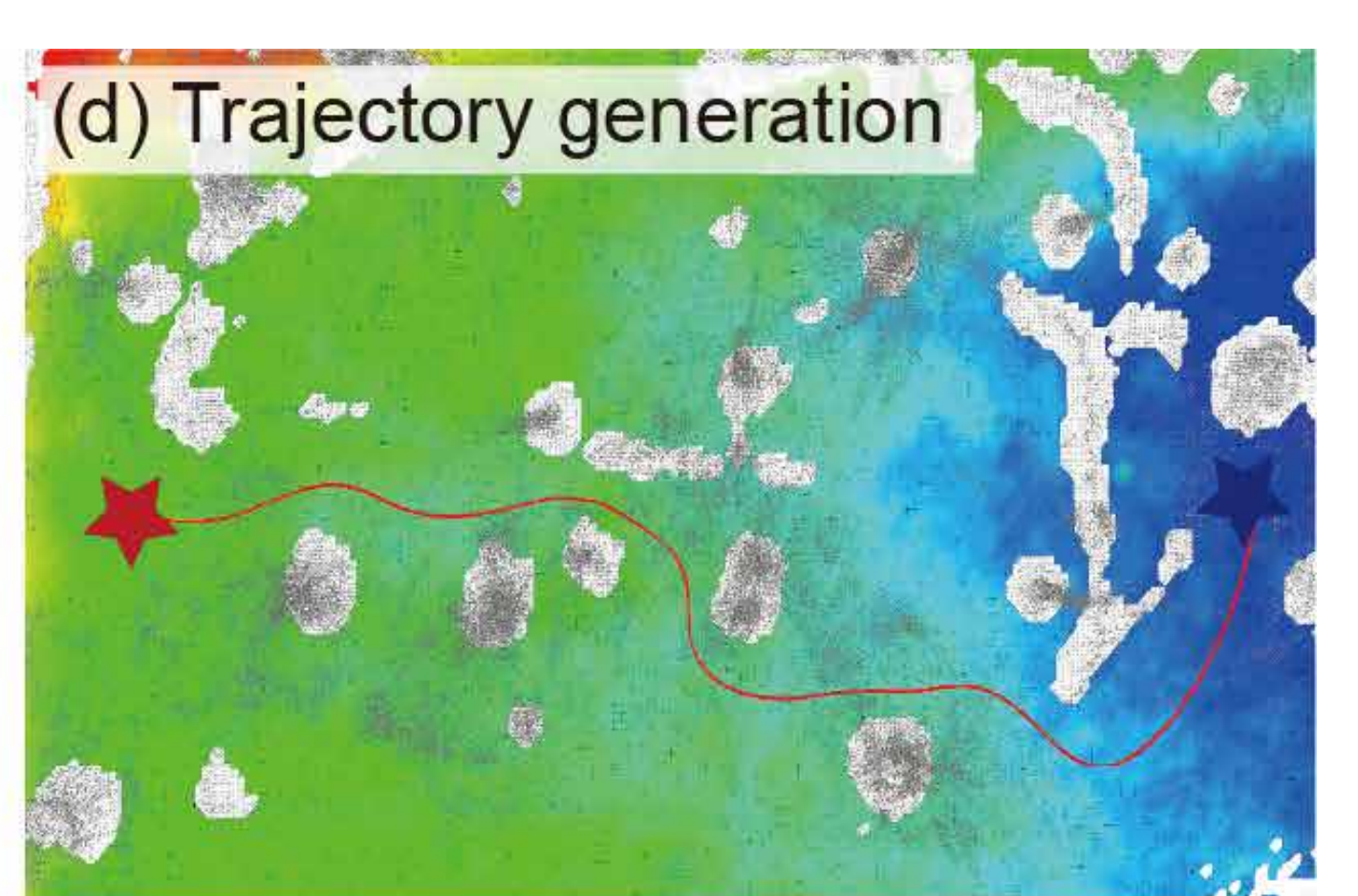
(b) Elevation map



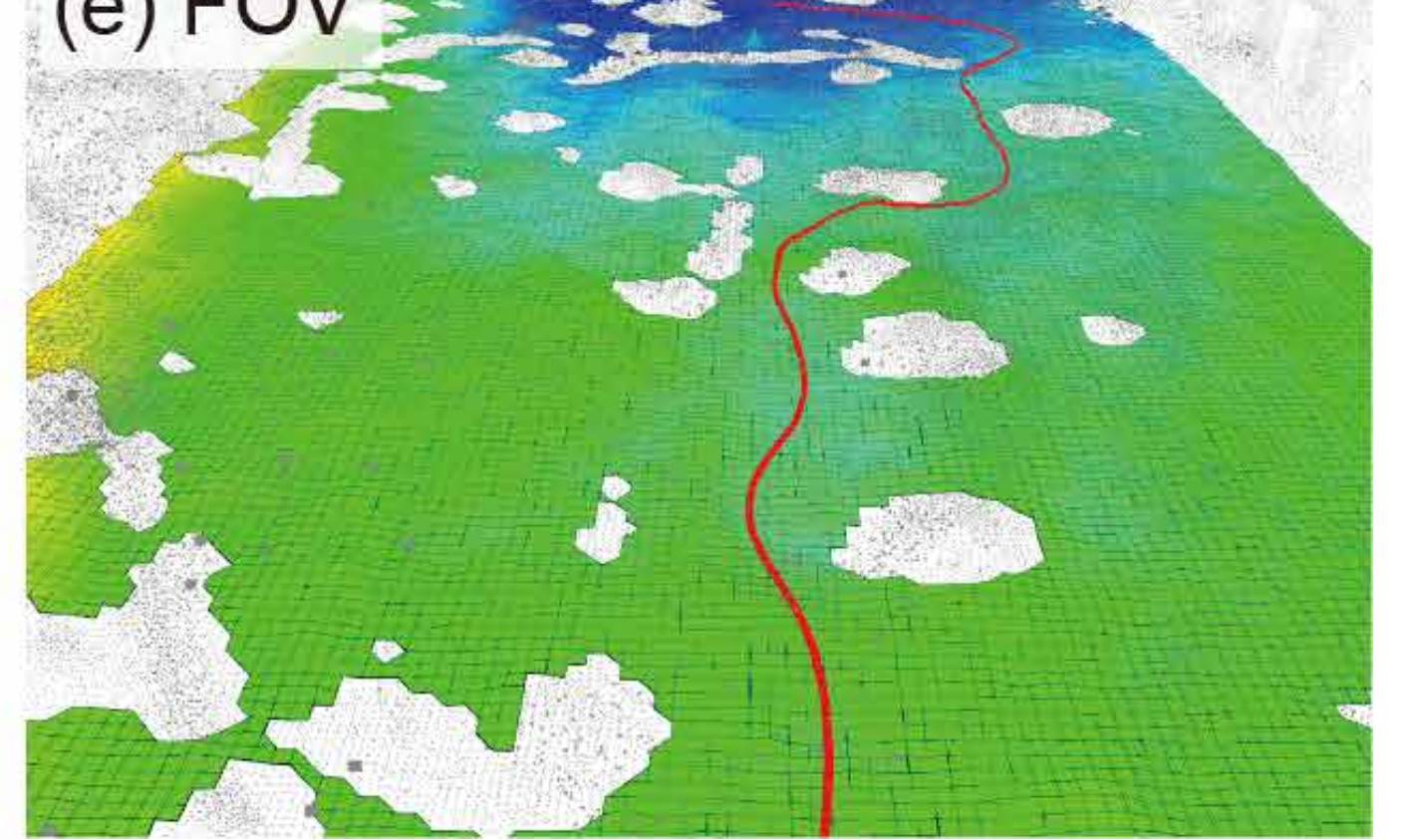
(a) Localized terrain



(c) Patch-RRT* & Safe corridor



(d) Trajectory generation



(e) FOV

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

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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