Online Adaptation of Terrain-Aware Dynamics

Planning in Unstructured Environments

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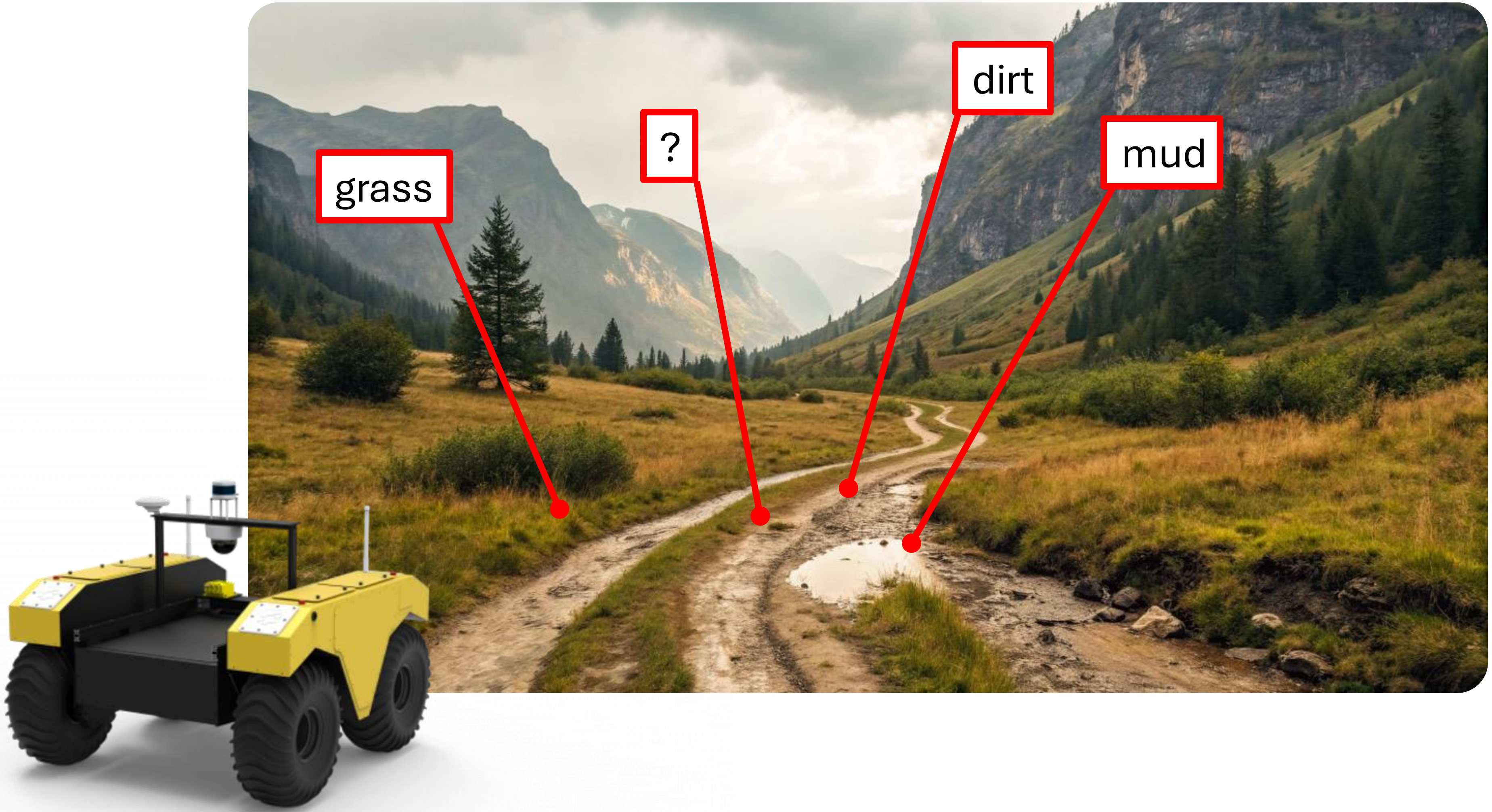
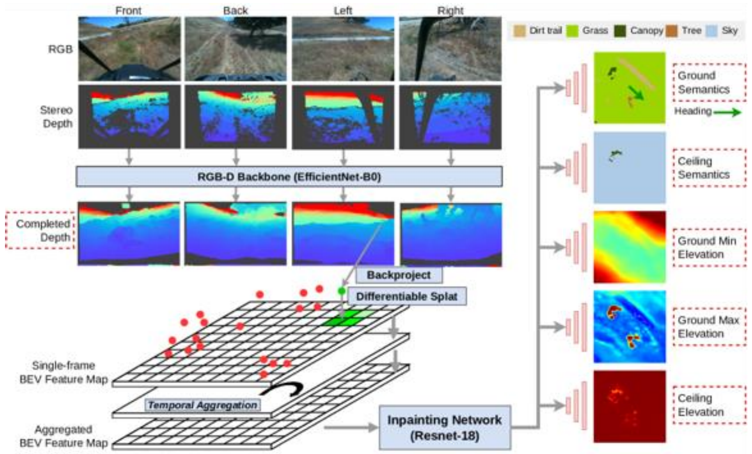
The Vision: adaptable autonomy in **unseen** environments

Adapting robots to new conditions at runtime

Problem: how can we adapt to different terrains?



Adaptation and transfer for robotics

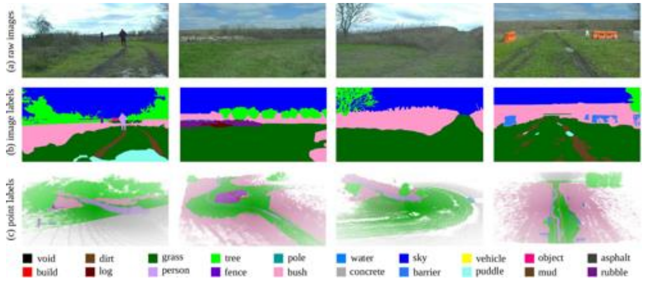


Mapping

X. Meng, N. Hatch, A. Lambert, A. Li, N. Wagener, M. Schmittle, J. Lee, W. Yuan, Z. Chen, S. Deng, G. Okopal, D. Fox, B. Boots, A. Shaban (2023). Terrainnet: Visual modeling of complex terrain for high-speed, off-road navigation.

Navigation

Han, T., Liu, A., Li, A., Spitzer, A., Shi, G., & Boots, B. (2023). Model predictive control for aggressive driving over uneven terrain.

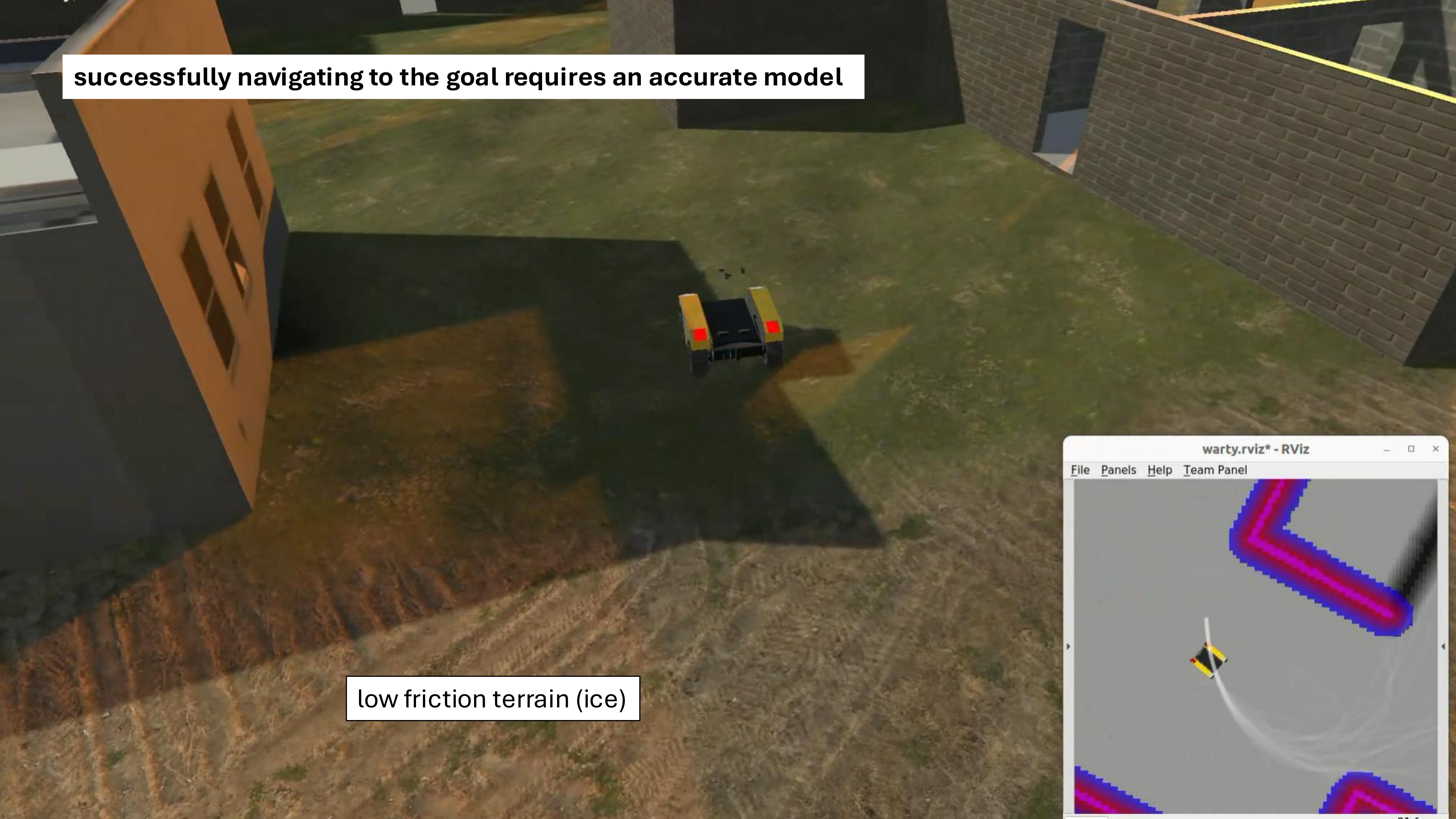


Semantic Segmentation

Jiang, P., Osteen, P., Wigness, M., & Saripalli, S. (2021). Rellis-3d dataset: Data, benchmarks and analysis

What’s missing?

an adaptive **model** of ***how*** the robot drives on different terrains


successfully navigating to the goal requires an accurate model
low friction terrain (ice)
warty.rviz* - RViz
File
Panels
Help
Team Panel

How can we identify a dynamics model at runtime using limited data?

Given:
- historical trajectories on varying terrains
- a small amount of online data

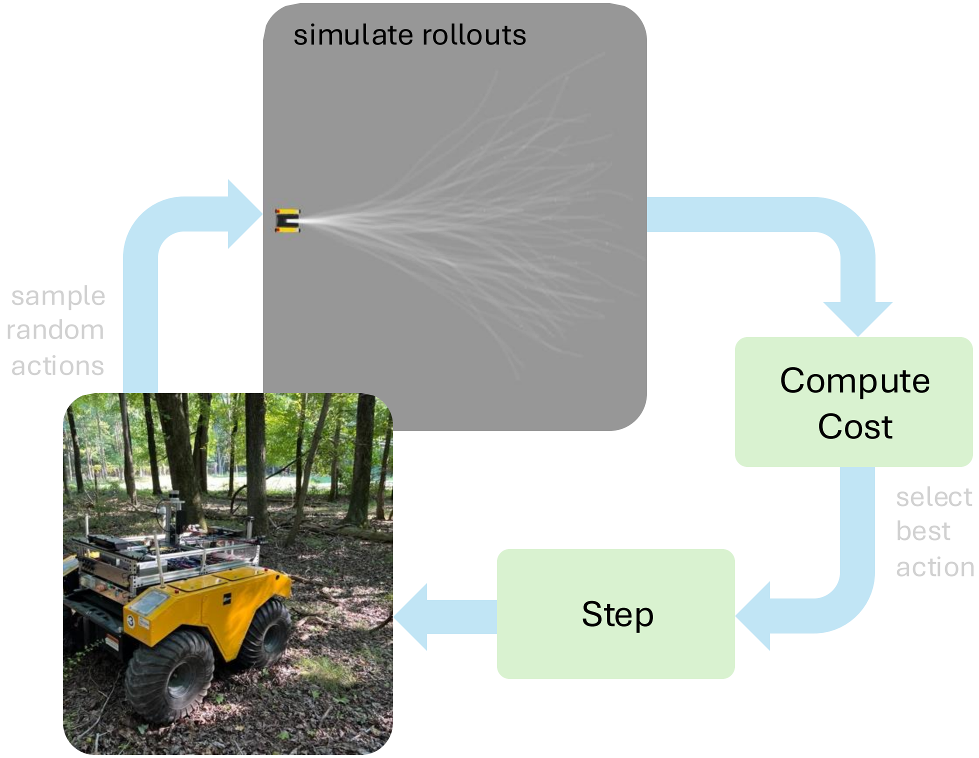
Goal: estimate dynamics $\dot{x}(t) = f^{w}(x(t), u(t), t)$

neural ODE

$$x(t) = x(0) + \int_0^t f_\theta(x(\tau), u(\tau), \tau) d\tau$$

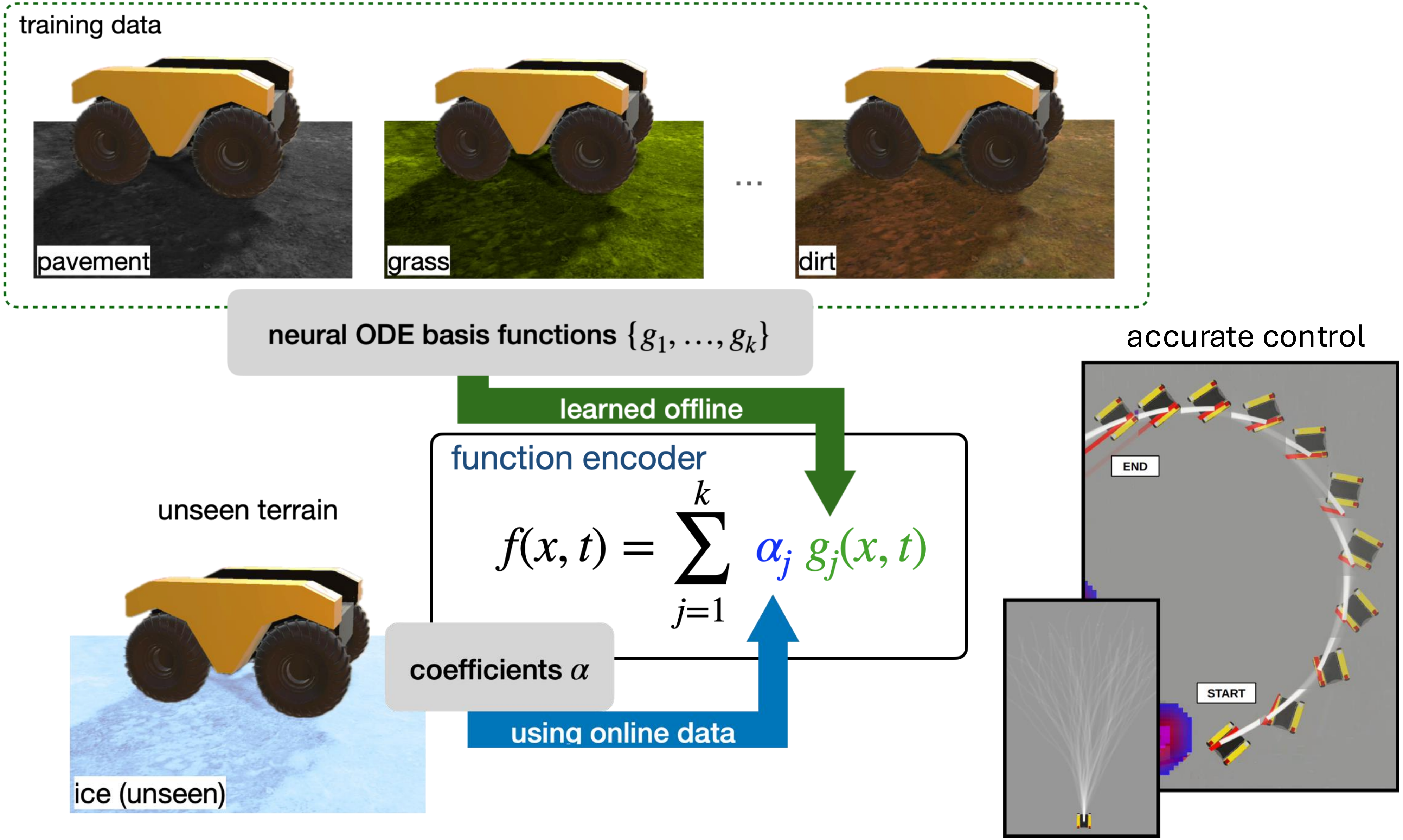
function encoder (our approach)

$$x(t) = x(0) + \sum_{j=1}^{k} \alpha_j \int_0^t g_j(x(\tau), u(\tau), \tau \mid \theta_j)\, d\tau$$



Ingebrand, T., Thorpe, A. J., & Topcu, U. (2024). Zero-shot transfer of neural ODEs. NeurIPS

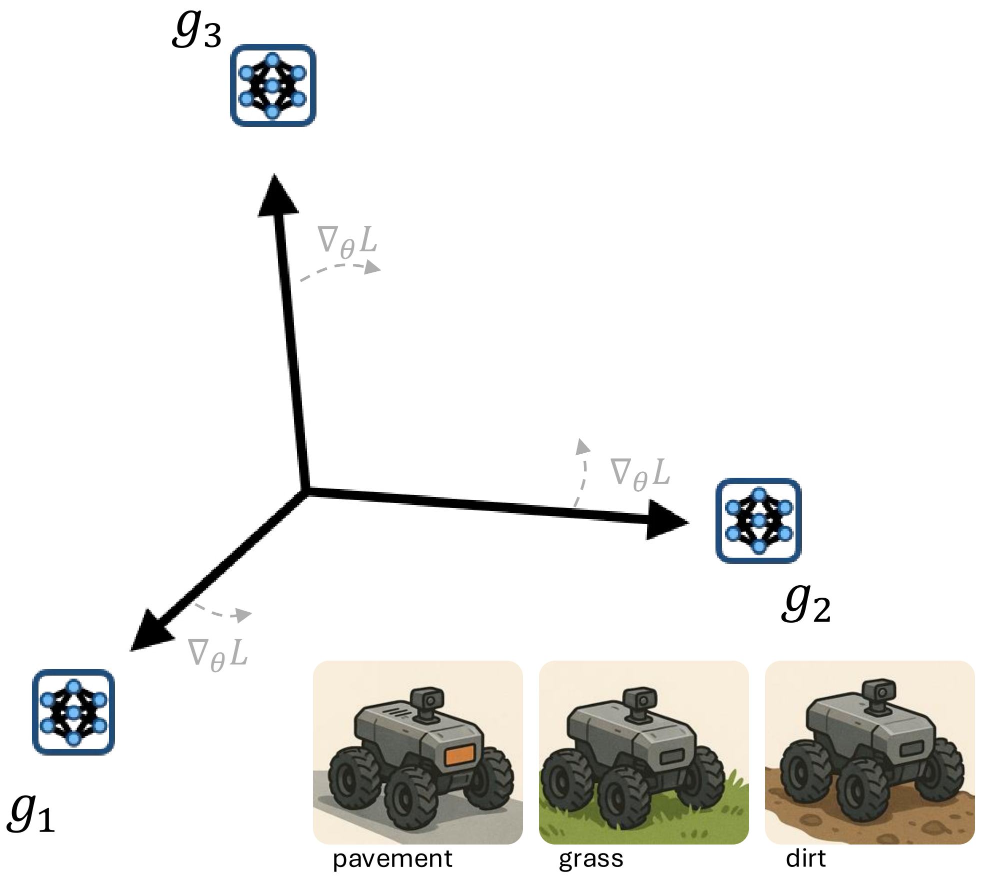
Learning a space of terrain-induced dynamics for online adaptation



Breaking function encoders down: **offline training, online inference**

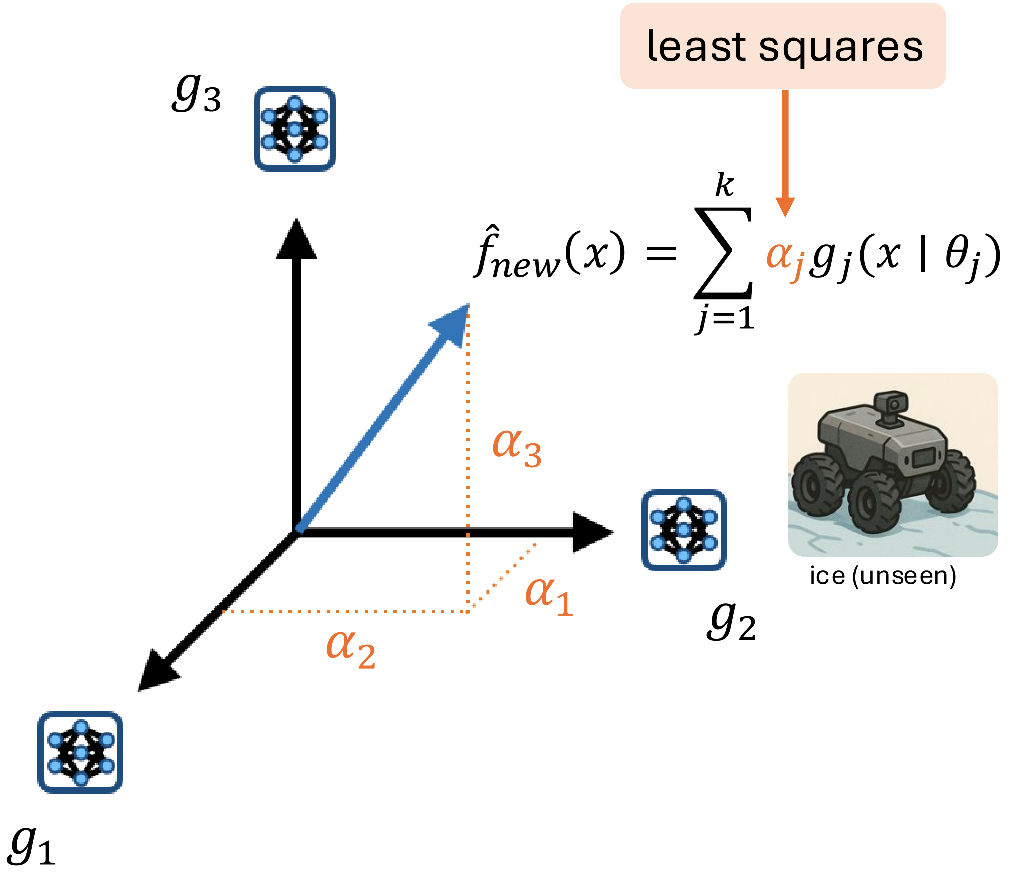
Offline Training

learn the basis functions



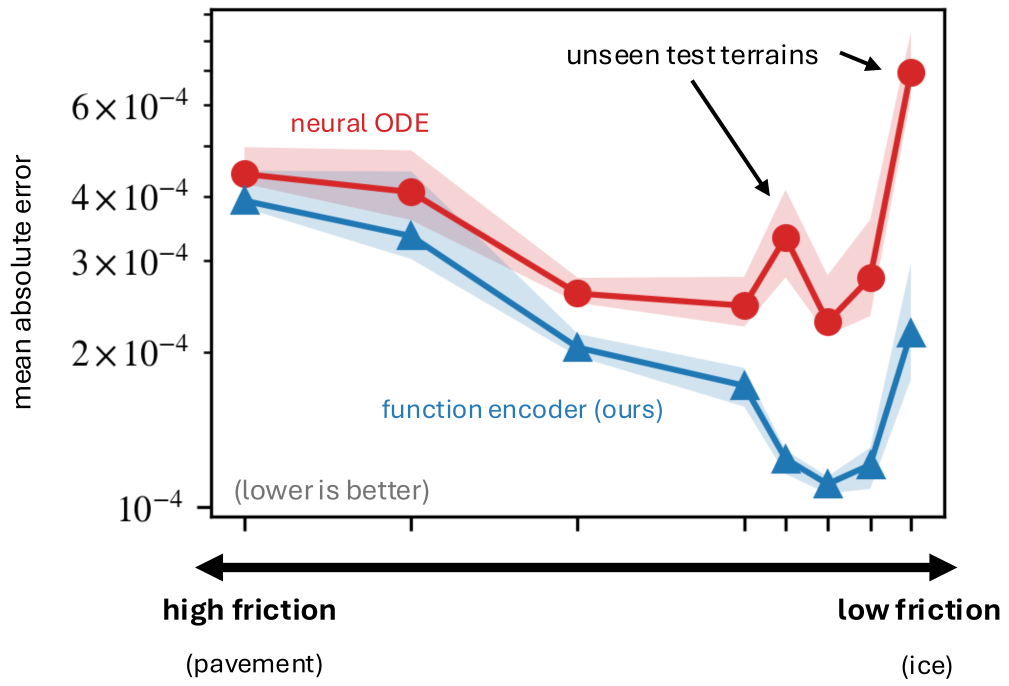
Online Inference

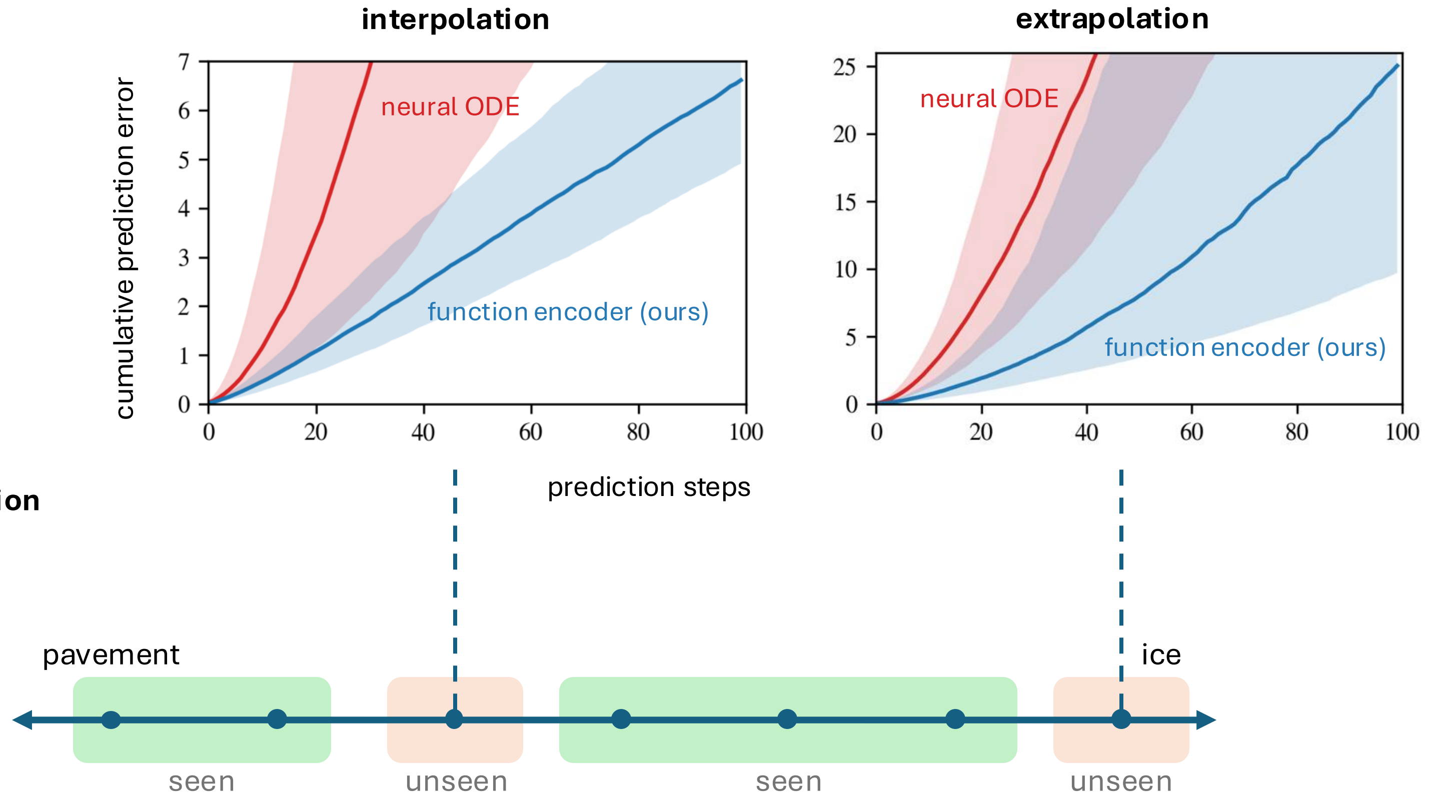
compute the coefficients α



Ingebrand, T., Thorpe, A. J., & Topcu, U. (2025). Function Encoders: A Principled Approach to Transfer Learning in Hilbert Spaces.

Function encoders adapt to varying terrains



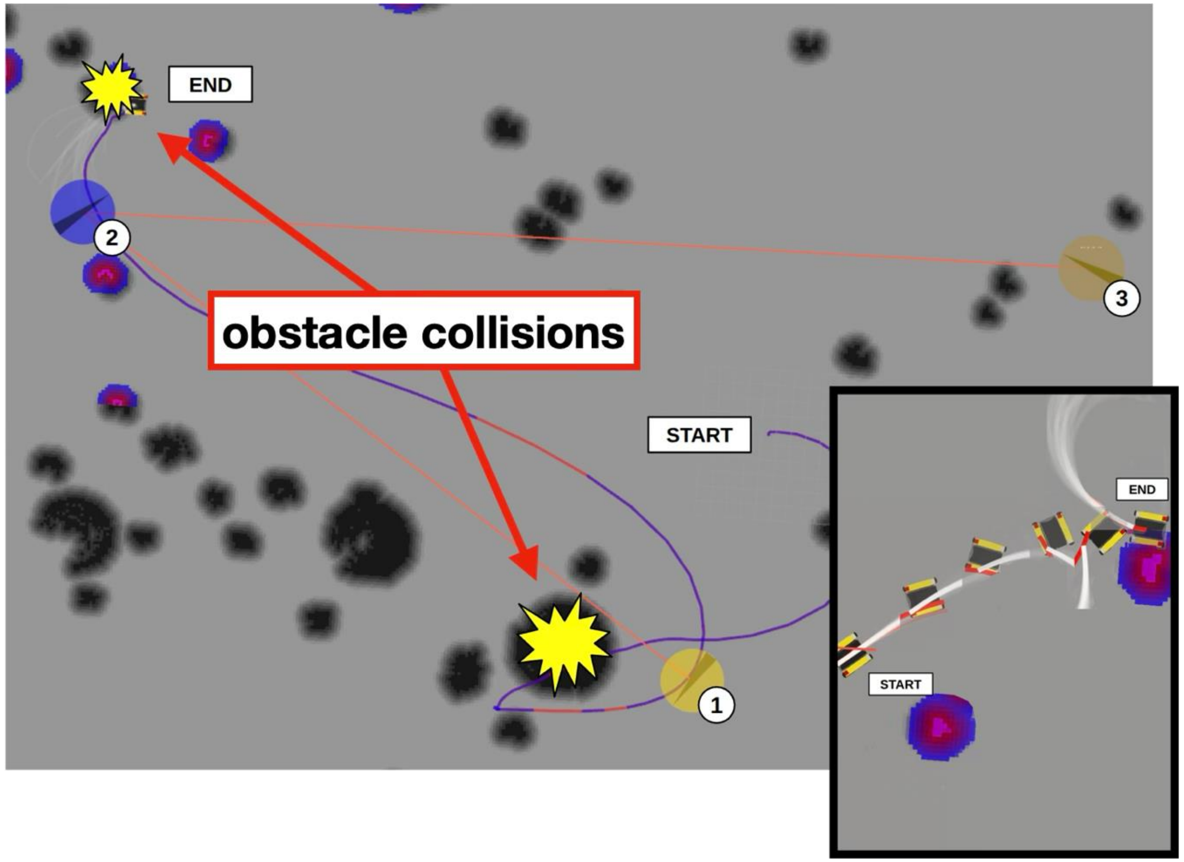


function encoders are more accurate because they **adapt**

Function encoders improve downstream control performance

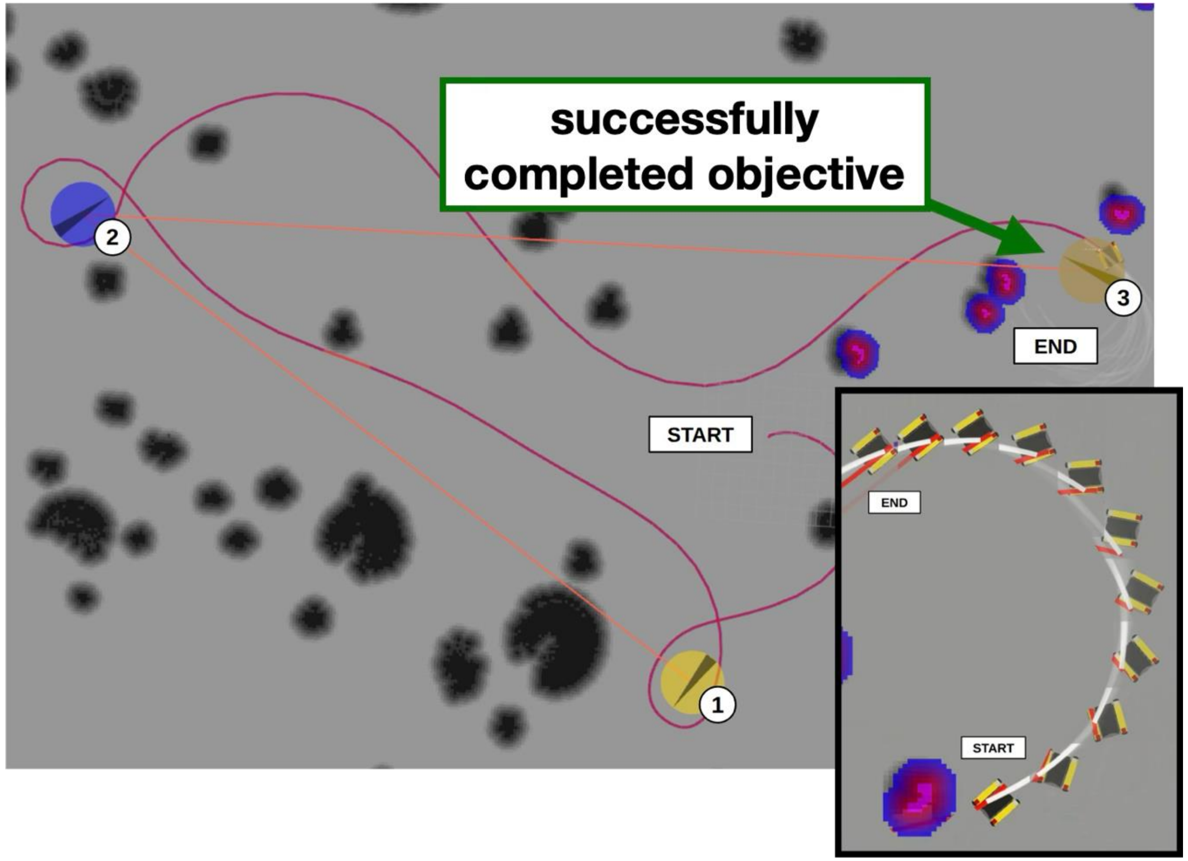
Accurate models are critical for **safe** control

neural ODE



inaccurate rollouts

function encoder (ours)



accurate rollouts

Given:

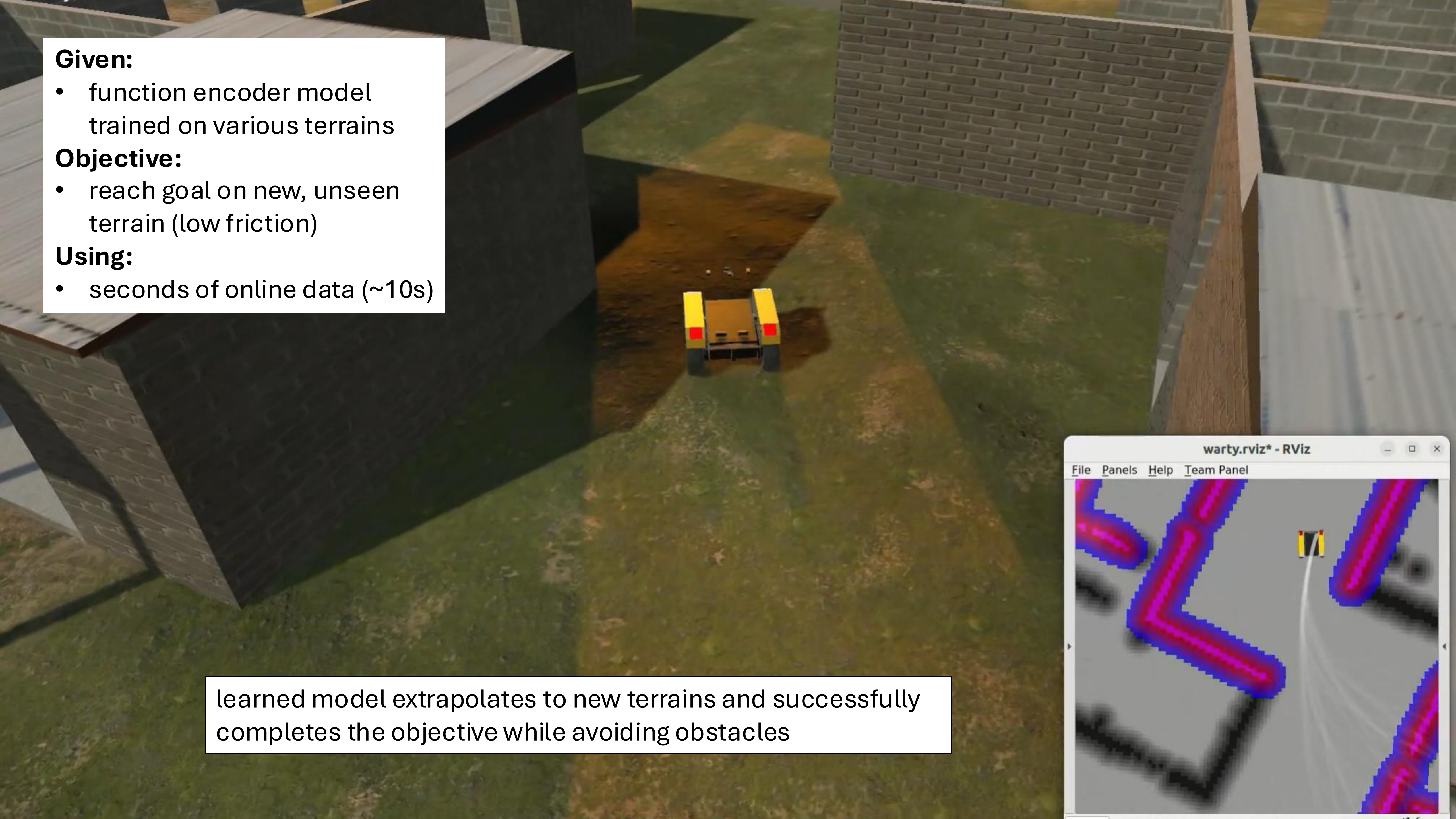
- function encoder model trained on various terrains

Objective:

- reach goal on new, unseen terrain (low friction)

Using:

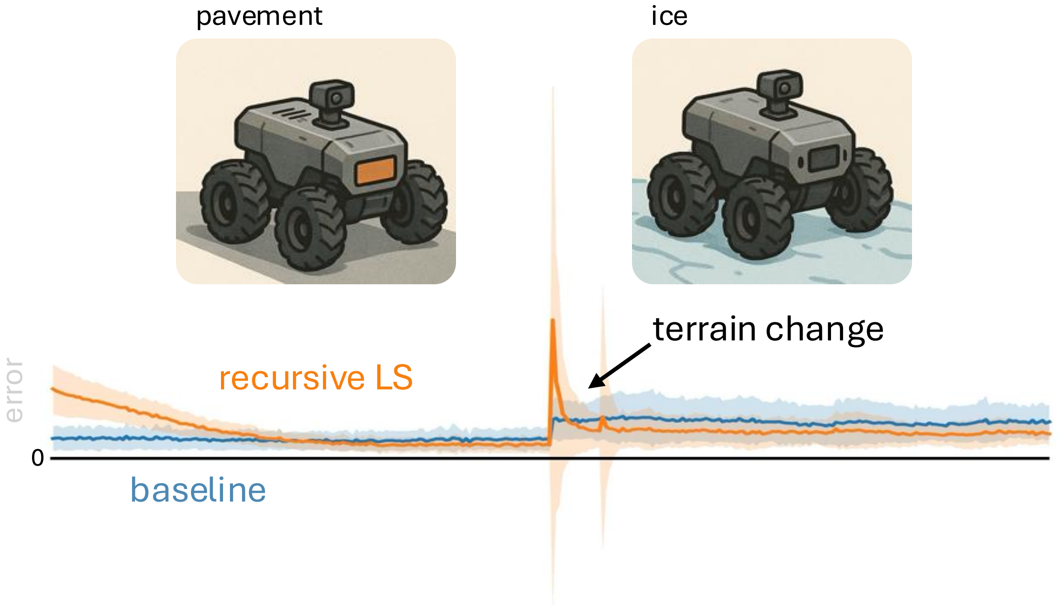
- seconds of online data (~10s)



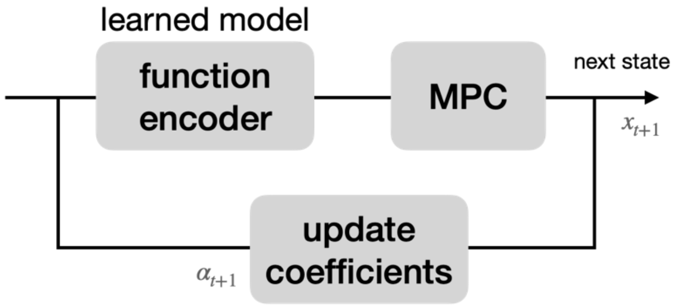
learned model extrapolates to new terrains and successfully completes the objective while avoiding obstacles

Real-time adaptation using recursive least squares

From zero to autonomy in **seconds.**



- we **only need to update the coefficients** to adapt
- can be performed **online** in real time
- handles **changing terrain** without retraining



Future Work: Vision to dynamics

Goal: estimate the robot dynamics from camera images