

# Variable-Resolution Virtual Map Guided Informed Tree Search for Autonomous USV Exploration

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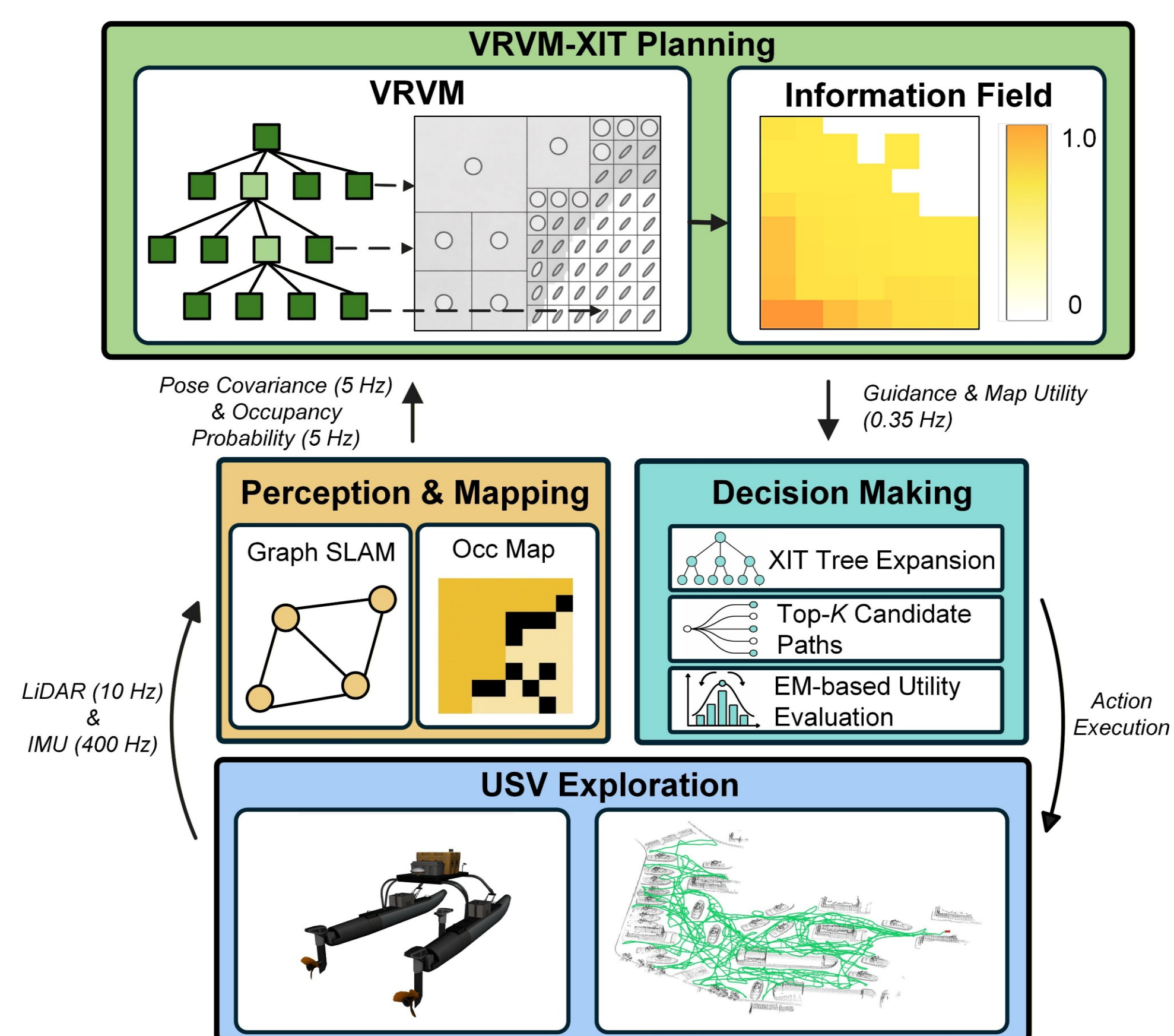
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## INTRODUCTION & MOTIVATION

- USV exploration near shore is not only about covering space; localization reliability also matters.
- VRVM-RRT evaluates uncertainty, but its candidate paths are still generated by random sampling.
- Random proposals can look exploratory, yet remain dispersed, redundant, and weakly aligned with map uncertainty.
- VRVM-XIT turns VRVM uncertainty into a continuous information field to guide tree expansion and trajectory generation.

## METHOD: VRVM - XIT



1: Normalize VRVM uncertainty into a continuous planning field:

$$U_t(\mathbf{p}) = \log \det(\Sigma_{\mathbf{v}_k(\mathbf{p})})$$

$$J_t(\mathbf{p}) = \frac{U_t(\mathbf{p}) - U_t^{\min}}{U_t^{\max} - U_t^{\min} + \varepsilon}$$

$$J_t(\mathbf{p}) \in [0, 1]$$

2: Evaluate how informative a tree edge is:

$$J_t(e) \approx \max_{m=0, \dots, M_e} J_t(\mathbf{p}_e^{(m)})$$

3: Edges through informative regions receive lower expansion cost:

$$c_t(e) = \alpha_d \ell(e) + \beta_i \ell(e)(1 - J_t(e))$$

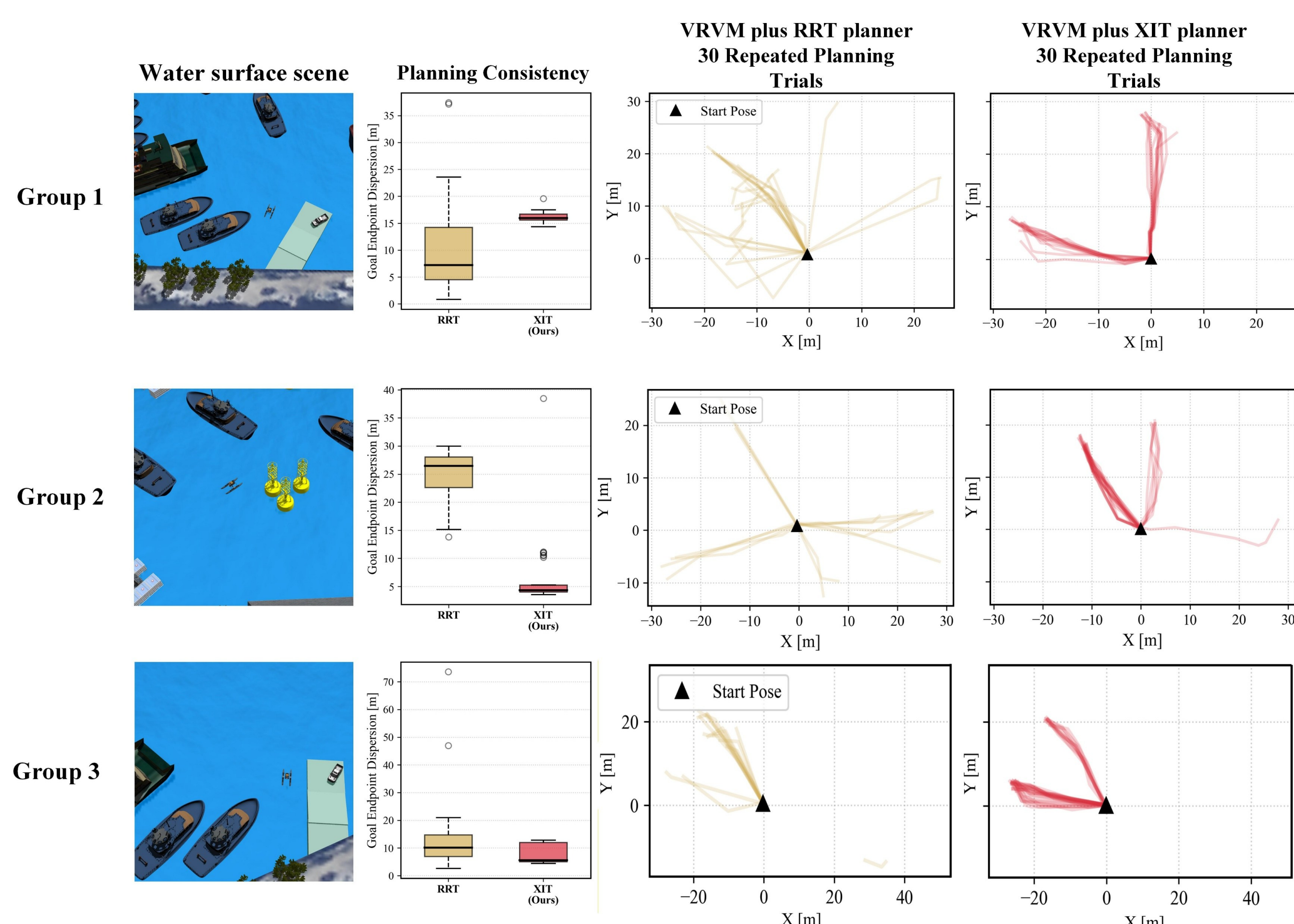
4: Top-K candidates are filtered by cost density; the final path is selected by virtual-map utility:

$$J_t(\pi) = \frac{G_t(\pi)}{L(\pi) + \varepsilon}, \quad G_t(\pi) = \sum_{e \in \pi} c_t(e),$$

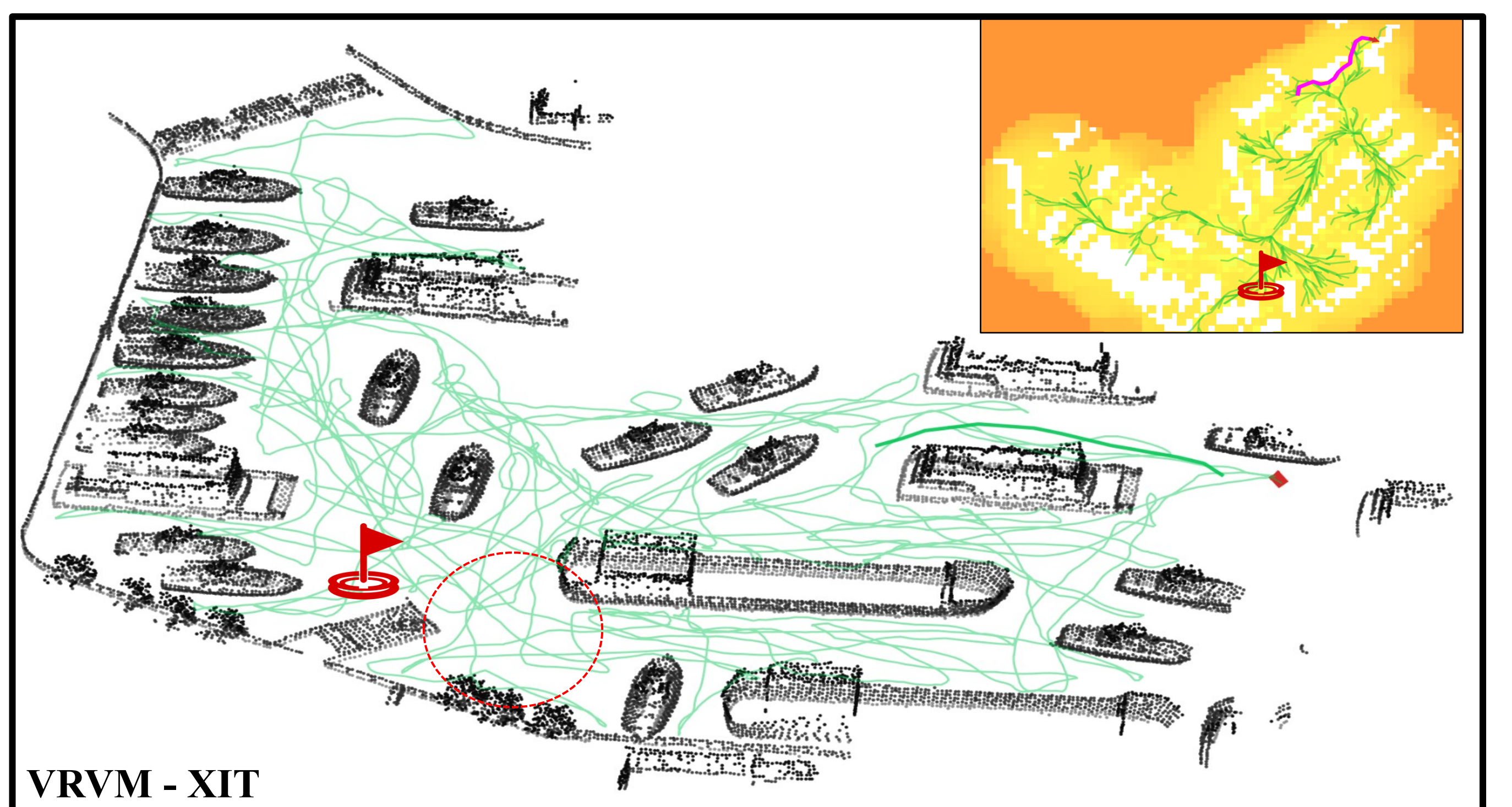
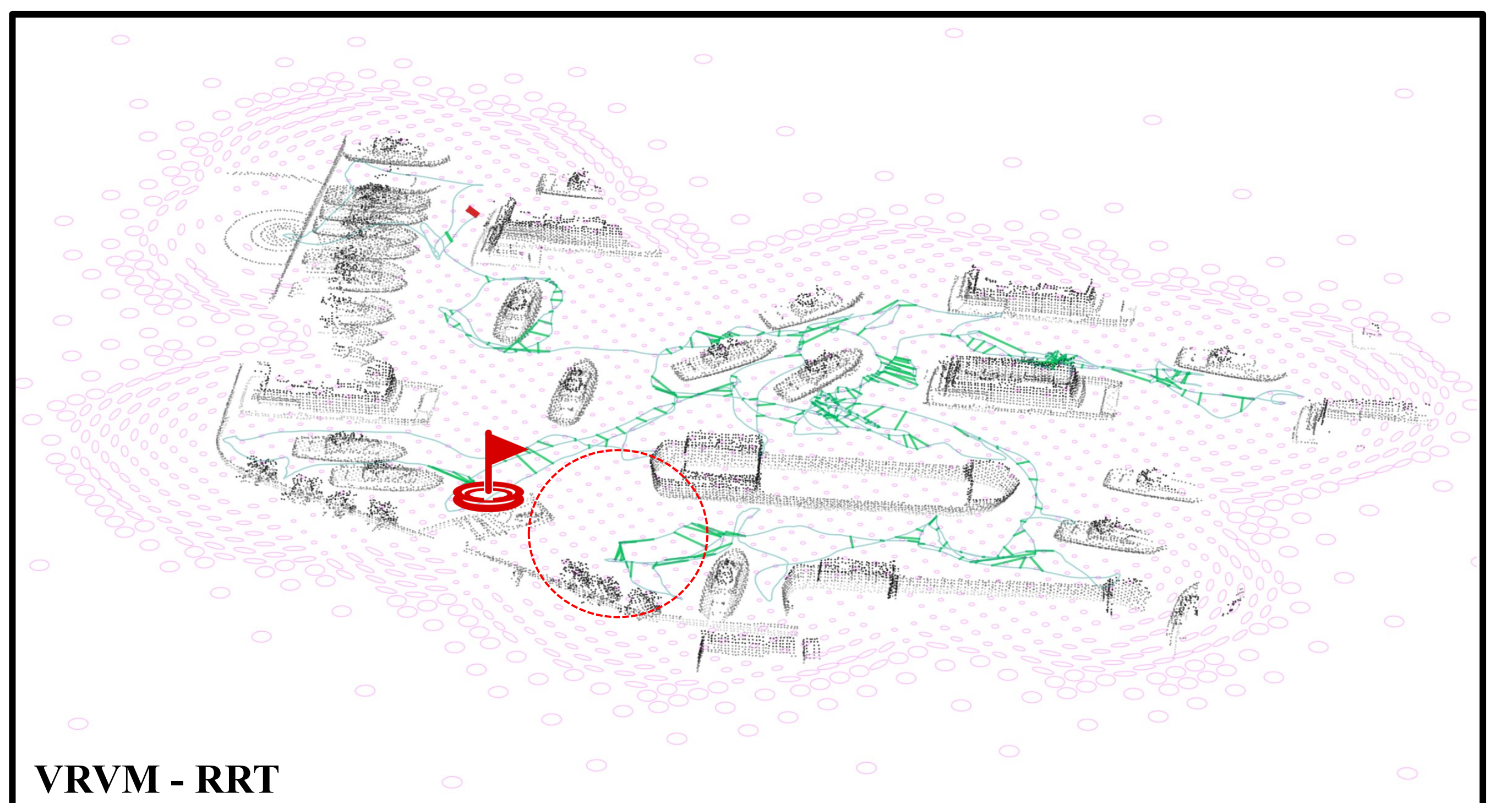
$$L(\pi) = \sum_{e \in \pi} \ell(e)$$

$$U_{EM}(\pi) = \beta U_{pose}(\pi) + \gamma U_{map}(\pi) - \alpha L(\pi)$$

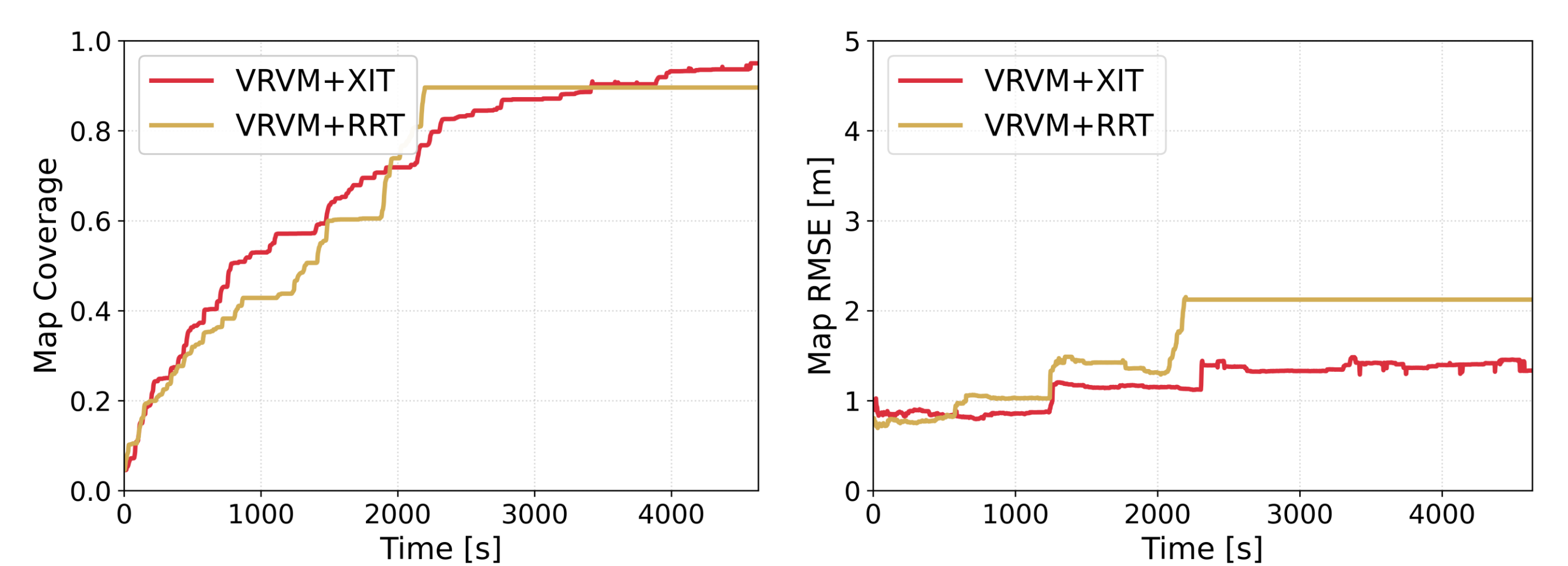
## LOCAL PLANNING CONSISTENCY



## LONG-HORIZON EXPLORATION BEHAVIOR



## REPRESENTATIVE QUANTITATIVE RESULTS



The comparison is made under the same exploration framework and target-coverage setting.

• VRVM-XIT reaches comparable or higher coverage while maintaining lower map error, indicating a better coverage-accuracy trade-off.

• This suggests that more consistent proposal generation can accumulate into better long-horizon exploration behavior.

## CONCLUSION & FUTURE WORK

• Planning consistency matters: over 30 repeated local trials, VRVM-XIT produced more structured and repeatable path families than VRVM-RRT.

• In the long-horizon run, VRVM-XIT reached higher map coverage (~0.95 vs. ~0.90) while maintaining lower map error (~1.3-1.4 m vs. ~2.1 m).

Future work will investigate how uncertainty-guided proposal generation can remain consistent under real-world sensing noise, actuation error, and GNSS-degraded near-shore conditions.

## References

- [1] Ye Li, Yewei Huang, Wenlong GaoZhang, Alberto Quattrini Li, Brendan Englot, and Yuanchang Liu, "Variable-Resolution Virtual Maps for Autonomous Exploration with Unmanned Surface Vehicles (USVs)," arXiv preprint arXiv:2603.22667, 2026.
- [2] Mal Fazliu, Matthew Coombes, Sen Wang, and Cunjia Liu, "XIT: Exploration and Exploitation Informed Trees for Active Gas Distribution Mapping in Unknown Environments," arXiv preprint arXiv:2602.13739, 2026.