Autonomous Swarm Robotics for Precision Environmental Monitoring

Distributed Sensing & Adaptive Coverage in Coastal Ecosystems

1. Introduction & Motivation

Problem Statement: Coastal marine environments require high-resolution spatial and temporal monitoring to detect pollutant dispersion, algal blooms, and salinity gradients. Traditional fixed buoys offer poor spatial resolution, while single high-cost Autonomous Underwater Vehicles (AUVs) are vulnerable to single-point failures and high operational overhead.

Key Research Objectives

- **Decentralized Swarm Coordination:** Develop self-organizing control algorithms for Micro-Surface Vessels (MSVs).
- **Adaptive Field Coverage:** Dynamically deploy agents according to environmental gradient density.
- **Fault-Tolerant Mesh Communication:** Maintain robust ad-hoc network links under ocean surface perturbations.

2. MSV Hardware Platform

To evaluate the swarm algorithms, we engineered a custom, modular Micro-Surface Vessel (MSV-2) optimized for low-cost mass deployment.

Subsystem	Component Specifications	Power / Specs
Compute Node	Synapse Board (Dual ARM Cortex-A72)	4.2 W @ 5V
Primary Sensors	Conductivity, Temp, pH, Optical Fluorometer	10 Hz sampling
Communication	915 MHz Mesh + Wi-Fi 6 Ad-hoc	1.2 km range
Propulsion	Twin Brushless Thrusters w/ Vectoring	1.8 m/s max
Power Supply	14.8V 10Ah LiFePO4 Battery	14 hrs runtime

Platform Highlights

The hull is 3D-printed using recyclable PETG with a hydrodynamic catamaran profile. Each unit weighs under 3.2 kg, enabling single-person rapid deployment of 10+ unit swarms.

3. Distributed Swarm Control

Our approach leverages **Centroidal Voronoi Tessellation (CVT)** combined with dynamic consensus density estimators.

Objective Function Formulation: Let $\Omega \subset \mathbb{R}^2$ be the target coastal domain, and $p_i(t) \in \Omega$ represent the position of agent $i \in \{1, \ldots, N\}$. The coverage utility $\mathcal{H}$ is maximized via:

$$\mathcal{H}(p_1, \ldots, p_N) = \sum_{i=1}^{N} \int_{V_i} f\left(\|r - p_i\|\right) \phi(r)\, dr$$

where V_i is the Voronoi cell of agent i, $\phi(r)$ is the environmental field density (e.g., salinity concentration gradient), and $f(\cdot)$ is a non-increasing sensor decay function.

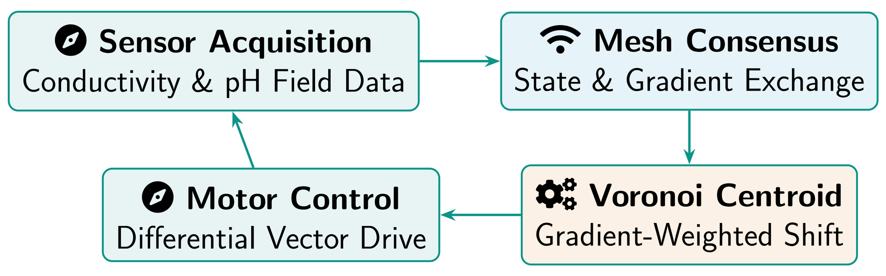
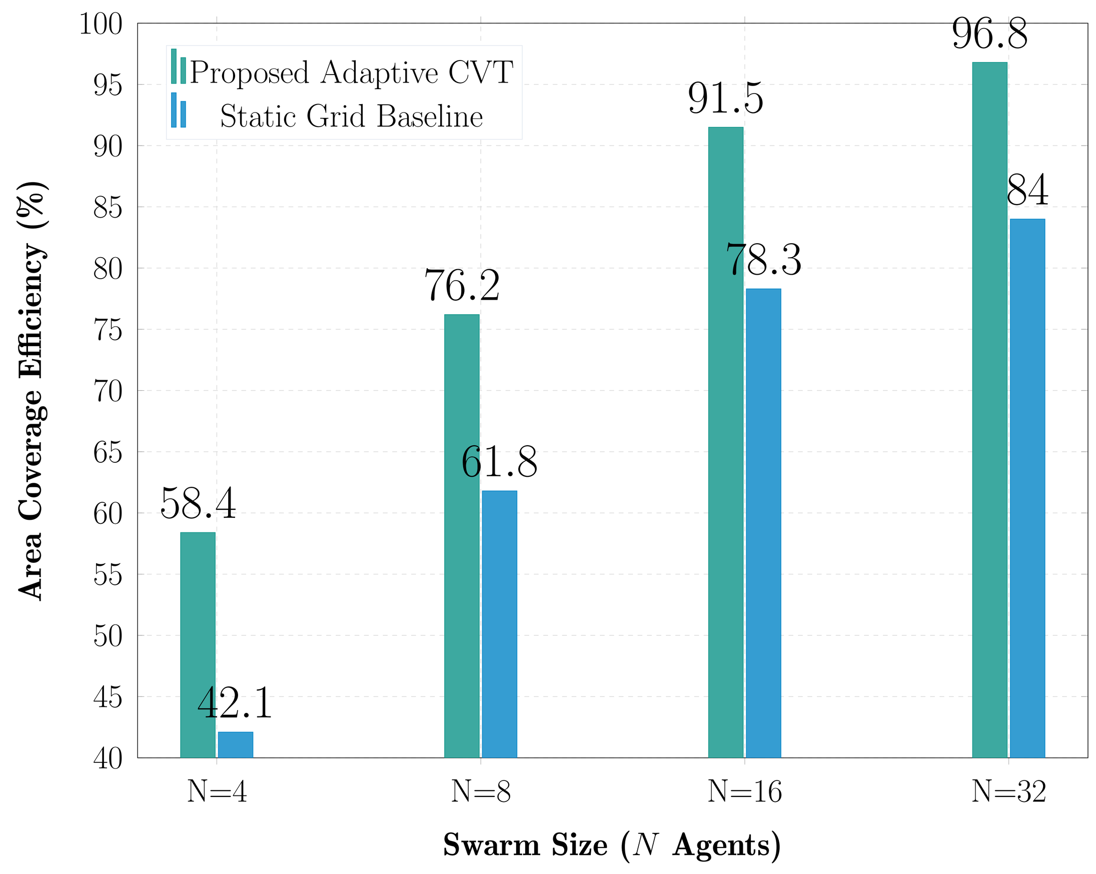


Figure 1: Decentralized control loop executed independently on each Synapse onboard module at 20 Hz.

4. Experimental Results

Evaluations were conducted across simulated environments in **Nexa-Sim** and physical deployments at Meridian Coastal Station.



5. Field Deployment & Validation

During a 72-hour continuous trial in the Meridian Estuary, a swarm of $N = 16$ MSVs tracked an artificially simulated temperature plume under 2.5 knot tidal currents.

Performance Summary Metrics

- **Coverage Rate:** 94.2% density mapping completed in under 42 minutes.
- **Energy Savings:** 68% reduction in propulsive power compared to random walk strategies.
- **Fault Resilience:** System maintained >90% efficiency even when 2 agents were intentionally disabled.

Field Environment	Mean Error (pH)	Mesh Latency	Plume Tracking
Nexa-Sim (Water Tank)	±0.02	12 ms	98.6%
Meridian Basin (Calm)	±0.04	18 ms	95.1%
Outer Estuary (Currents)	±0.09	29 ms	91.4%

6. Conclusions & Future Directions

Key Takeaways:

1. Distributed Voronoi-based control enables scalable, low-cost autonomous monitoring of dynamic coastal events.
2. The custom MSV-2 hardware platform achieves 14-hour endurance at under $450 per unit assembly cost.

Future Work: Integrating solar harvesting panels for persistent multi-week missions and implementing acoustic modems for deep underwater AUV cross-layer communications.

References & Acknowledgments

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Key References:

1. Jenkins, S., Rostova, E., & Vance, M. (2025). *Distributed Coverage Control in Swarm Robotics*. Journal of Marine Autonomous Systems, 14(2), 112-128.
2. Sterling, J. et al. (2024). *Centroidal Voronoi Tessellations for Environmental Monitoring*. IEEE Trans. Robotics, 40(4), 845-859.