

Balancing **Expansion** and **Contraction**

Coordinating Multi-Agent Teams Under Competing Goals

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Technion, Israel Institute of Technology



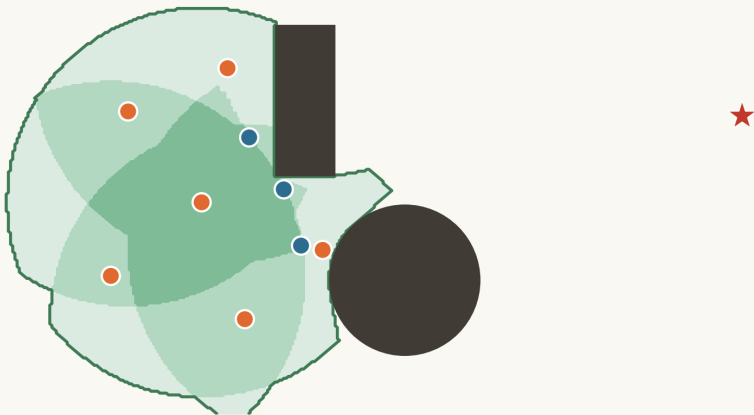
CLAWAR 2026 · Exploration, Resilience and Recovery

01

The vision

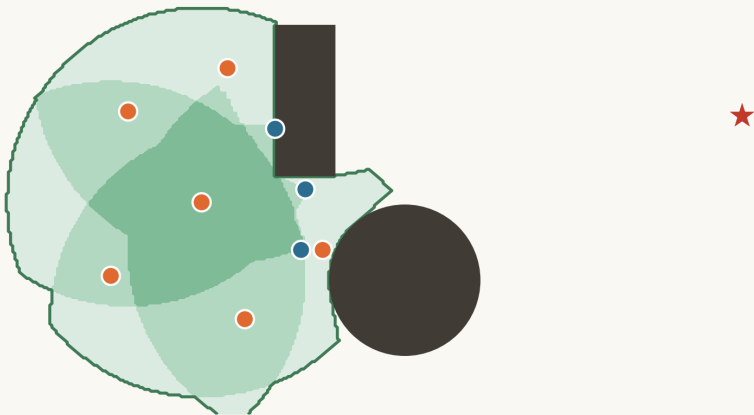
A team that carries its own frame of reference
into unknown ground.

Anchor migration, one cycle at a time



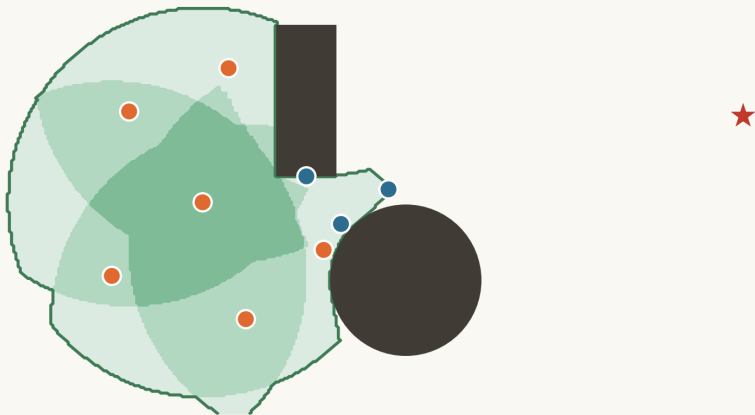
Explore. Anchors hold; explorers move out, deep inside the region.

Anchor migration, one cycle at a time



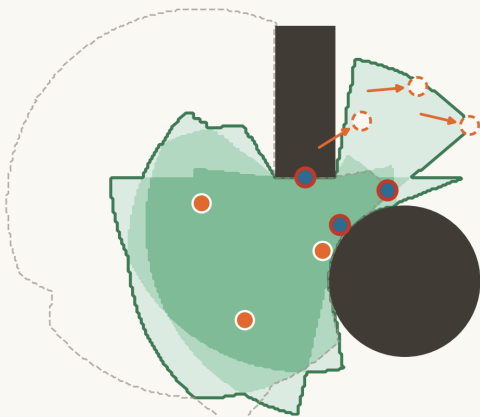
Advance. Further out: fewer anchors in view, the margin thins.

Anchor migration, one cycle at a time



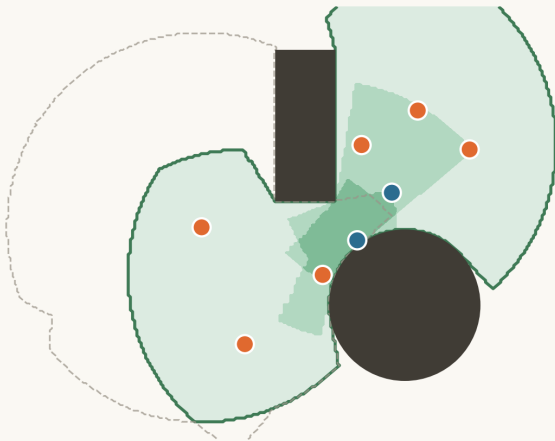
Margin reached. Three anchors left. The region has run out.

Anchor migration, one cycle at a time



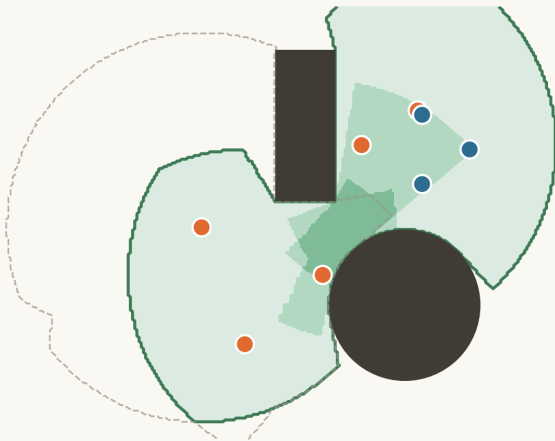
Relocate. Explorers freeze and anchor the frontier; the rear anchors migrate.

Anchor migration, one cycle at a time



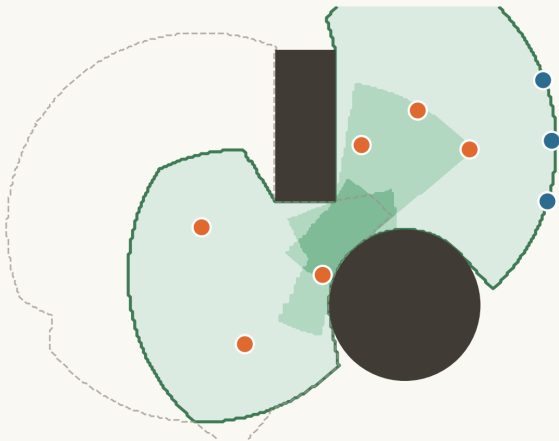
Explore. New anchor set, new region, carried forward.

Anchor migration, one cycle at a time



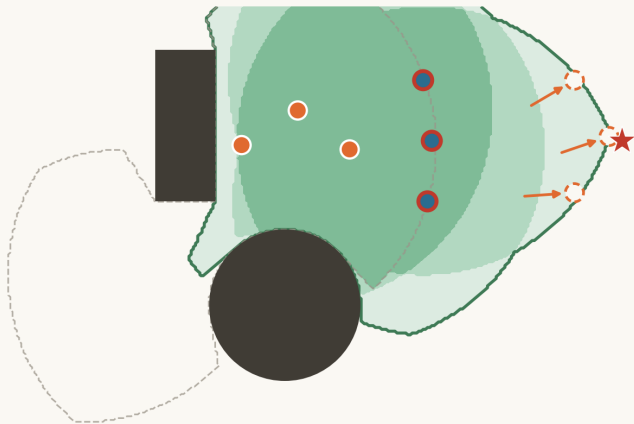
Advance. Past the wall, around the cylinder.

Anchor migration, one cycle at a time



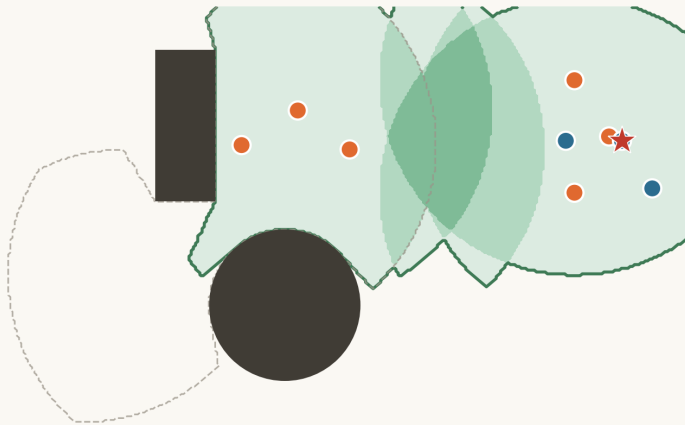
Margin reached. Again three anchors. Switch again.

Anchor migration, one cycle at a time



Relocate. Second migration, this time toward the goal.

Anchor migration, one cycle at a time



Goal reached. The team never left ground it could trust.

Communication is **patchable**: you can drop relays as you go.

Localization is **not**.

So localizability is a **scarce, spatially bounded resource** the team has to manage on purpose.

DARPA SubT: teams dropped mesh nodes like breadcrumbs to keep talking.
Nobody could drop a GPS satellite. (Ackerman, *IEEE Spectrum*, 2022)

02

The paper

One narrow question, answered: how do you trade **spreading out** against **staying together**?

To make it tractable, we stripped it down

THE VISION

- Obstacles deform the region
- Anchor/explorer roles swap
- GPS-denied, UWB-only
- Behaviour adapts per phase

THIS PAPER

- No obstacles
- No role split: all agents move
- Agents are GPS-localized
- One fleet-wide α

The GPS assumption is the single biggest gap.

UWB builds the ranging graph, not the estimate.

One objective, one knob

$$\max_{\mathbf{p}_i(t)} J_i^\gamma = \alpha \underbrace{M_E(\mathcal{G}_{\mathcal{N}_i}, \mathbf{p}_{\mathcal{N}_i})}_{\text{coverage}} + (1 - \alpha) \underbrace{M_C(\mathcal{G}_{\mathcal{N}_i}, \mathbf{p}_{\mathcal{N}_i})}_{\text{connectivity}} \quad \text{s.t. } (\mathcal{G}_{\mathcal{N}_i}, \mathbf{p}_{\mathcal{N}_i}) \in \mathcal{F}_{\mathcal{N}_i}$$

M_E : coverage

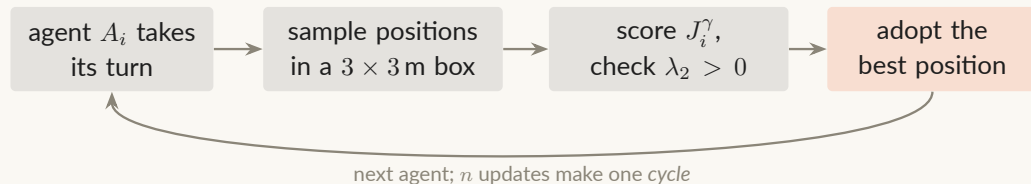
$1 - \mathcal{R}/\overline{\mathcal{R}}$: the inverse of cumulative quadratic repulsion. A *repulsive* potential.

M_C : connectivity

λ_2 of the normalized Laplacian. An *attractive* potential. Feasibility is $\lambda_2 > 0$.

Both normalized to $[0, 1]$, the only reason a single α is a meaningful weight.

Solved per agent, decentralized

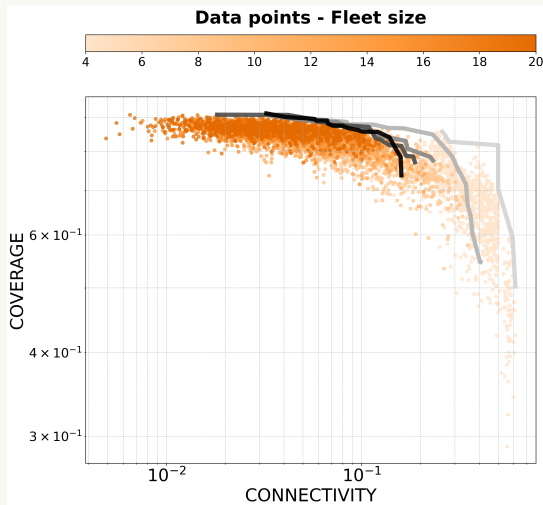


Each agent sees only its neighbourhood $\mathcal{N}_i$, and assumes it static during its turn.

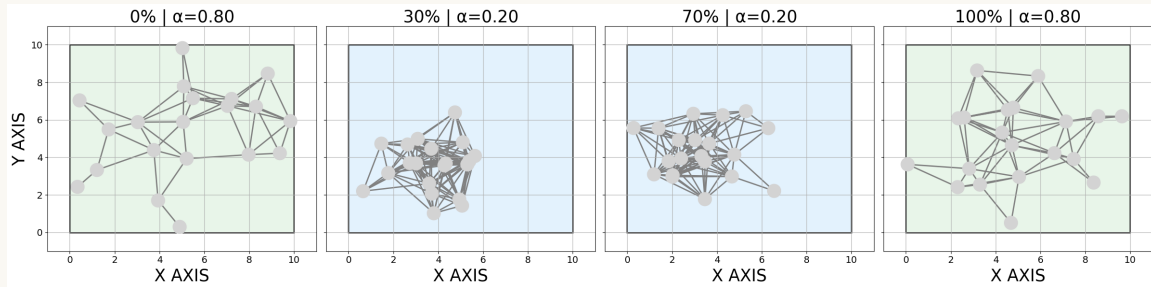
30 solver iterations, Optuna (NSGA-II), ≈ 0.04 s per update on an i7-13700H.

The trade-off is real, not assumed

- 1000 connected frameworks per fleet size
- $n = 4, 8, \dots, 20$ in a $10 \times 10 \text{ m}^2$ box
- A clear frontier: you cannot maximize both
- Larger fleets shift the feasible set *down* in connectivity



α dials the fleet

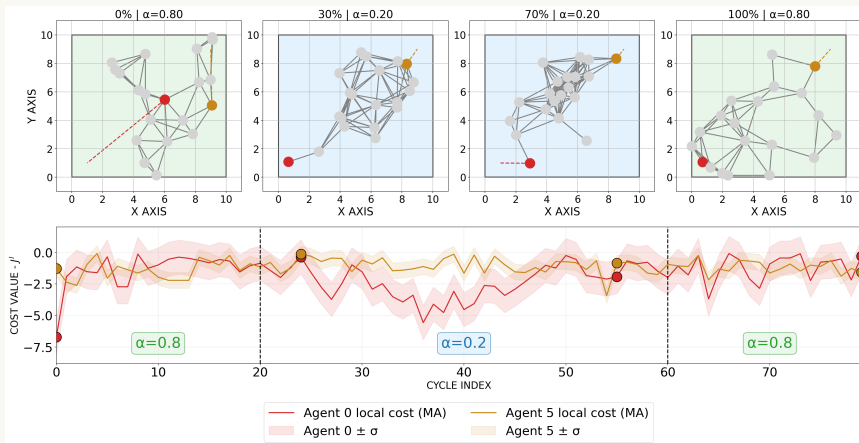


20 agents, 80 cycles, $\delta = \delta_M = 3$ m. Background **green** for **expansion**, **blue** for **contraction**.

$\alpha > 0.5$ **expands**

$\alpha < 0.5$ **contracts**

When a local goal fights the global topology



Two agents are sent to opposite corners, $J_i^l = -\|p_{\text{tgt},i} - p_i\|$. During **expansion** they reach their waypoints; during **contraction** connectivity pulls them back out.

Robustness to noise

Metric ($\mu \pm \sigma$)	Deterministic (0.00, 0.00)	Moderate (0.03, 0.10)	Severe (0.05, 0.20)
Coverage M_E ($\alpha = 0.8$)	0.889 ± 0.002	0.889 ± 0.001	0.888 ± 0.002
Connectivity M_C ($\alpha = 0.2$)	0.159 ± 0.023	0.128 ± 0.030	0.125 ± 0.028
Time fully connected [%]	100 ± 0.0	74.8 ± 14.5	71.1 ± 13.7

50 Monte Carlo runs. (σ_p, σ_m) in metres: actuation noise, UWB ranging noise.

The metrics hold. What degrades is *time fully connected*, the limit of passive recovery.

Where this sits, and what it is not

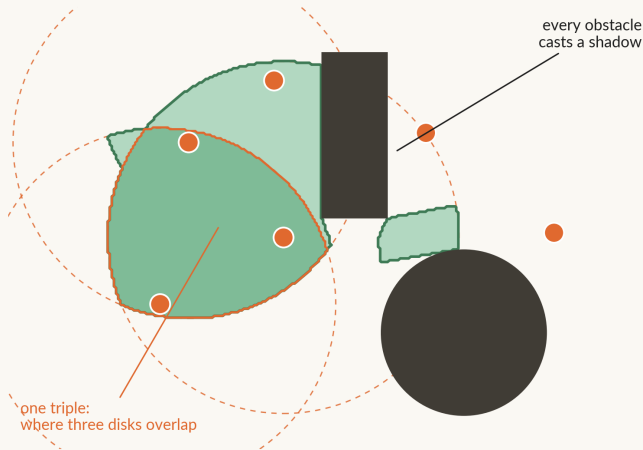
Approach	Motion	Limitation
TEAM Clark et al., ICRA 2021	One mover at a time	Exploration halts at every step; evaluated obstacle-free
Rigidity maintenance Zelazo et al., RSS 2012	Continuous	Localizable by construction, but no coverage objective
Connectivity fields Zavlanos & Pappas, 2007	Continuous	Connectivity as a hard constraint pins the fleet at full stretch
This work	Continuous, tunable	No localization, no obstacles (yet)

03

Where it goes

Putting the controller back inside the cycle it was carved out of.

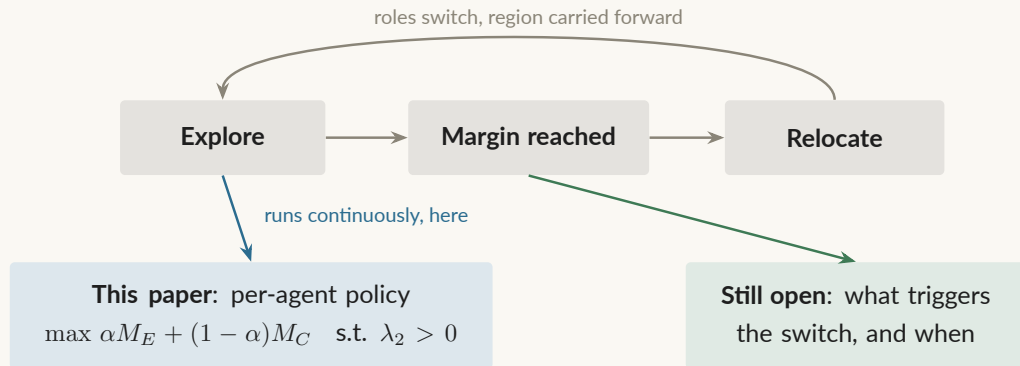
The region is the union of every three-anchor overlap



Today this is **binary**: three anchors in view, or none of it counts.

We propose to make it **graded and obstacle-aware**.

Where the paper plugs in



The controller we just showed is the **inner loop**. The migration cycle is the outer one.

A candidate backbone: containment control

The mapping

- **Anchors** → leaders
- **Explorers** → followers
- Followers converge into the leaders' convex hull
- Dynamic leaders fit migrating anchors

The honest caveats

- Most results sense leader *positions*; ours is range-only
- Hull membership is **not** a localizability certificate

Pair them: $L(\eta)$ as the certificate, containment control as the convergence guarantee.

Cao & Ren, 2009.

Roadmap



This paper · *done*

Coverage against
connectivity, with GPS.

MSc thesis · *proposed*

Localizability field and
anchor migration.

Hardware

Six Jackals, real UWB.
SAR and inspection.

Also on the paper's own list: analytical gradients on λ_2 for scale, and fading-weight propagation of local goals.

The team's most precious resource in a
GPS-denied environment
isn't battery, and it isn't bandwidth.

It's **the ground it can trust
under its own feet.**

Thank you. Questions?

Balancing **Expansion** and **Contraction**

Oliva, Zelazo, Degani

CLAWAR 2026

`federicoo@campus.technion.ac.il`

`github.com/CearLab/ActiveLoc`

The animated anchor-migration cycle is on the repo.

[1] Oliva, Zelazo, Degani. CLAWAR 2026.

[2] Kuprian. *Active Anchor Migration for Multi-Agent Collaborative Exploration in GPS-Denied Environments*. MSc proposal, Technion, 2026.

[3] Clark et al. *TEAM*. ICRA 2021.

[4] Cao, Ren. *Containment control with multiple stationary or dynamic leaders*. 2009.

[5] Ackerman. *Robots conquer the underground*. IEEE Spectrum, 2022.

Backup: the full behavioural sweep

Three fleet-wide pairings (α_{exp} , α_{con}), 80 cycles each:

Pairing	α	Behaviour
Strong	(1.0, 0.0)	Full dispersion against full clustering
Mild	(0.8, 0.2)	The sequence shown in the talk
Weak	(0.6, 0.4)	Narrow swing; fleet stays mid-density

In all three the fleet traverses the empirical Pareto space rather than sitting at a corner of it, which is the tunability claim.

Backup: setup and cost

Simulation

$n = 20$ agents

$10 \times 10 \text{ m}^2$ workspace

$\delta = \delta_M = 3 \text{ m}$

80 cycles per run

Solver

Optuna, NSGA-II sampler

30 iterations per agent turn

$3 \times 3 \text{ m}$ local sampling box

$\approx 0.04 \text{ s}$ per update (i7-13700H)

One *cycle* = one sequential sweep over all n agents.

Code: github.com/CearLab/ActiveLoc

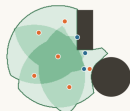
Backup: the whole march

Explore



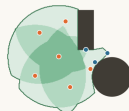
Anchors hold. Explorers move out, deep inside the localizable region.

Advance



Further out, fewer anchors in view — the margin is thinning.

Margin reached



Only three anchors left in view — the region has run out.

Relocate — cycle 1



Roles switch: the hubbed explorers anchor the frontier, the rear anchors migrate.

Explore



Anchors hold. Explorers move out, deep inside the localizable region.

Advance



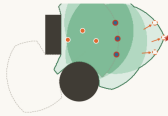
Further out, fewer anchors in view — the margin is thinning.

Margin reached



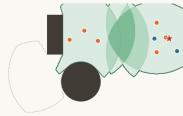
Only three anchors left in view — the region has run out.

Relocate — cycle 2



Roles switch: the hubbed explorers anchor the frontier, the rear anchors migrate.

Goal reached



The region now covers the goal. The team never left ground it could trust.