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DisCoverage: From Coverage to Distributed Multi-Robot Exploration

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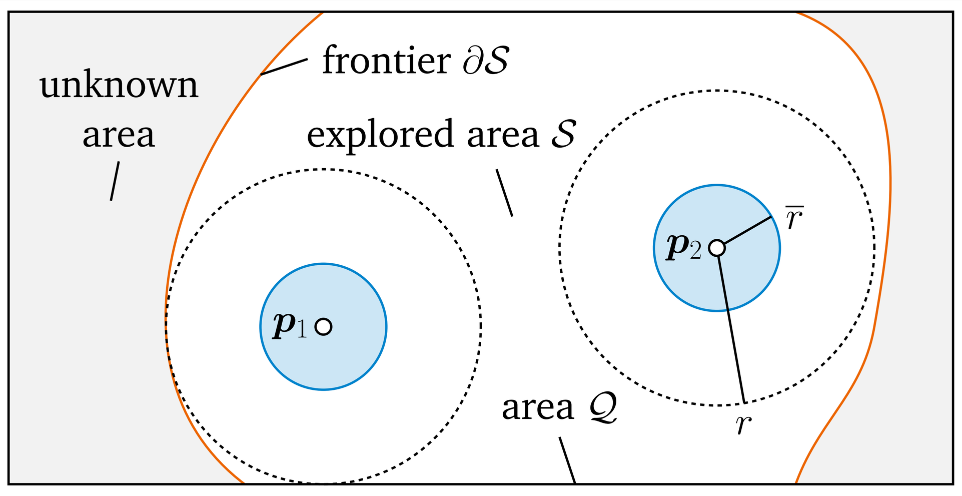
REGELUNGSTHEORIE UND ROBOTIK rtr

Motivation



- explore convex environment $\mathcal{Q}$ with N robots
- frontier-based [4], distributed control laws

$\Rightarrow$ goal: $\mathcal{S}(t) \to \mathcal{Q}$ for $t \to \infty$

Our Approach: DisCoverage

Transfer the solution to the **coverage problem** [2, 3] to the exploration problem.

$\Rightarrow$ coverage + exploration = DisCoverage

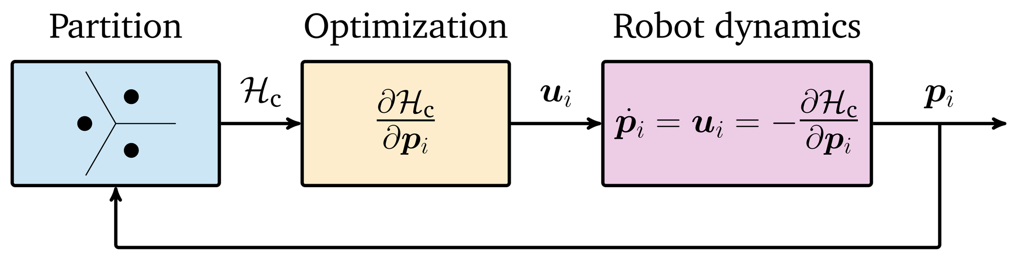
a fully distributed approach to multi-robot exploration

Set-up and Definitions

- robot position $\boldsymbol{p}_i \in \mathbb{R}^n$
- simple robot dynamics $\dot{\boldsymbol{p}}_i = \boldsymbol{u}_i$ with control input $\boldsymbol{u}_i$
- $\mathcal{P} := \{\boldsymbol{p}_1, \dots, \boldsymbol{p}_N\}$
- Voronoi cell $\mathcal{V}_i := \{\boldsymbol{q} \in \mathcal{Q} \mid \|\boldsymbol{q} - \boldsymbol{p}_i\|_2 \le \|\boldsymbol{q} - \boldsymbol{p}_j\|_2, \forall j\}$
- explored space $\mathcal{S}(t) \subseteq \mathcal{Q}$ and $\mathcal{S}_i(t) := \mathcal{S}(t) \cap \mathcal{V}_i$
- $\partial\mathcal{S}_i(t)$ denoting the frontier in Voronoi cell $\mathcal{V}_i$

Background: Solution to the Coverage Problem [1, 2, 3]

1. distributed Voronoi partition of the environment
2. distributed optimization of an objective function $\mathcal{H}_c$
3. motion control laws $\boldsymbol{u}_i$ solving the coverage problem



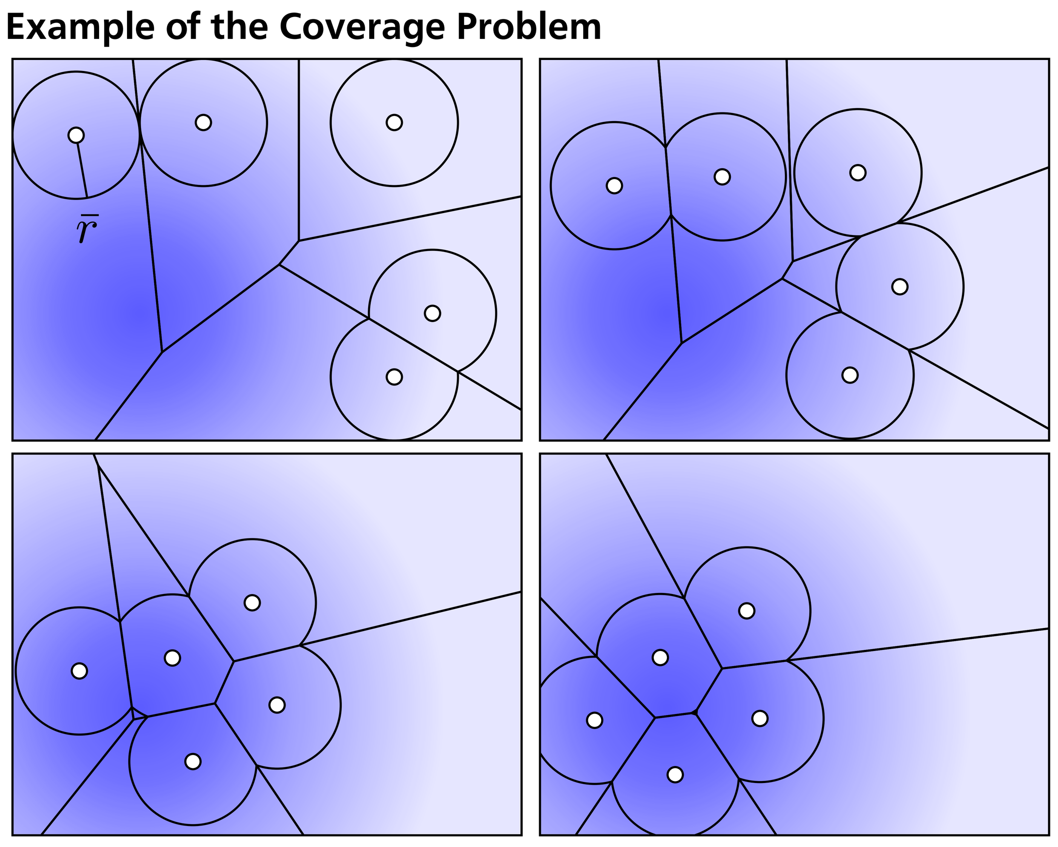
Objective Function

$$\mathcal{H}_c(\mathcal{P}) = \sum_{i=1}^{N} \int_{\mathcal{V}_{i,\overline{r}}} \|\boldsymbol{p}_i - \boldsymbol{q}\|_2^2 \, \phi(\boldsymbol{q}) \, d\boldsymbol{q} \;+\; R$$

$$\dot{\boldsymbol{p}}_i = \boldsymbol{u}_i = -\frac{\partial \mathcal{H}_c(\mathcal{P})}{\partial \boldsymbol{p}_i} = k_i \left(\mathrm{CM}_\phi(\mathcal{V}_{i,\overline{r}}) - \boldsymbol{p}_i\right)$$

- $\mathrm{CM}_\phi(\mathcal{V}_{i,\overline{r}})$: center of mass of $\mathcal{V}_{i,\overline{r}}$
- density function $\phi(\boldsymbol{q})$: expected information gain in $\boldsymbol{q}$

Example of the Coverage Problem



DisCoverage

Idea

- adapt $\mathcal{H}_c$ to facilitate distributed multi-robot exploration

$$\mathcal{H}_{dc}(\mathcal{P}, \mathcal{S}) = \sum_{i=1}^{N} \int_{\mathcal{V}_{i,\overline{r}}} \|\boldsymbol{p}_i - \boldsymbol{q}\|_2^2 \, \phi(\boldsymbol{q}, \partial\mathcal{S}_i) \, d\boldsymbol{q} \;+\; R$$

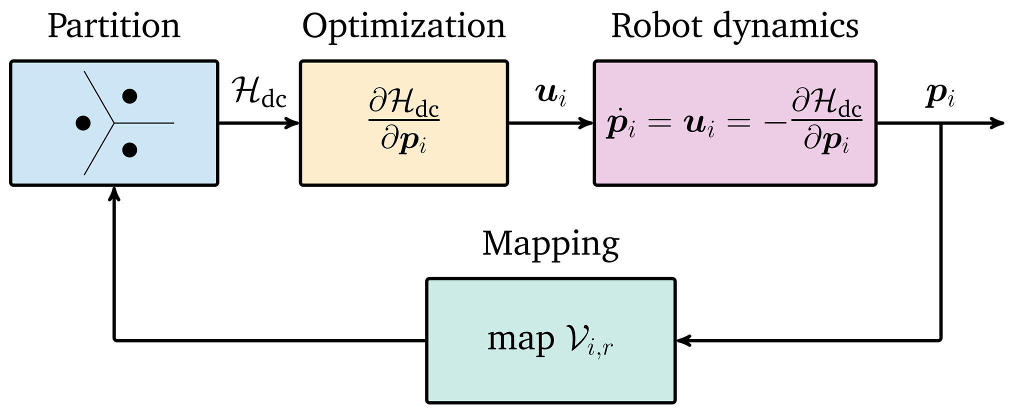
- density ϕ as a function of the time-varying frontier $\partial\mathcal{S}_i$

$$\phi(\boldsymbol{q}, \partial\mathcal{S}_i(\mathcal{P}(t), t)) = \exp\left(-\frac{1}{2\sigma^2} \operatorname{dist}^2(\boldsymbol{q}, \partial\mathcal{S}_i)\right)$$

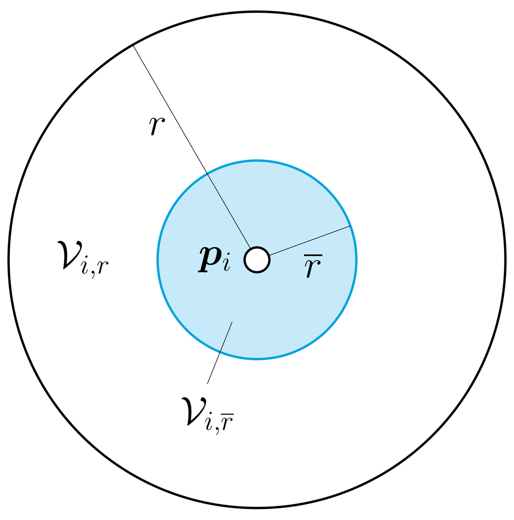
- density ϕ is quasi-stationary, therefore

$$\dot{\boldsymbol{p}}_i = \boldsymbol{u}_i = -\frac{\partial \mathcal{H}_{dc}(\mathcal{P}, \mathcal{S})}{\partial \boldsymbol{p}_i} = k_i \left(\mathrm{CM}_\phi(\mathcal{V}_{i,\overline{r}}) - \boldsymbol{p}_i\right)$$

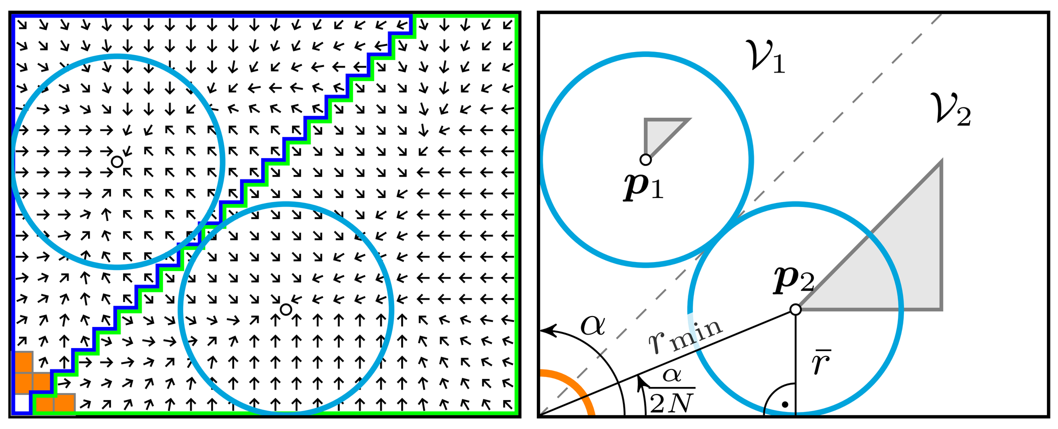
DisCoverage Feedback Loop



- map with sensing range r (not integration range $\overline{r}$)



Sensing Range



- border of $\mathcal{V}_i$ and $\partial\mathcal{Q}$ acts as repulsive force
- $\overline{r}$ enforces *reachability set* in $\mathcal{Q}$

$\Rightarrow$ **Required minimum sensing range:**

$$r_{\min} = \frac{\overline{r}}{\sin(\frac{\alpha}{2N})}$$

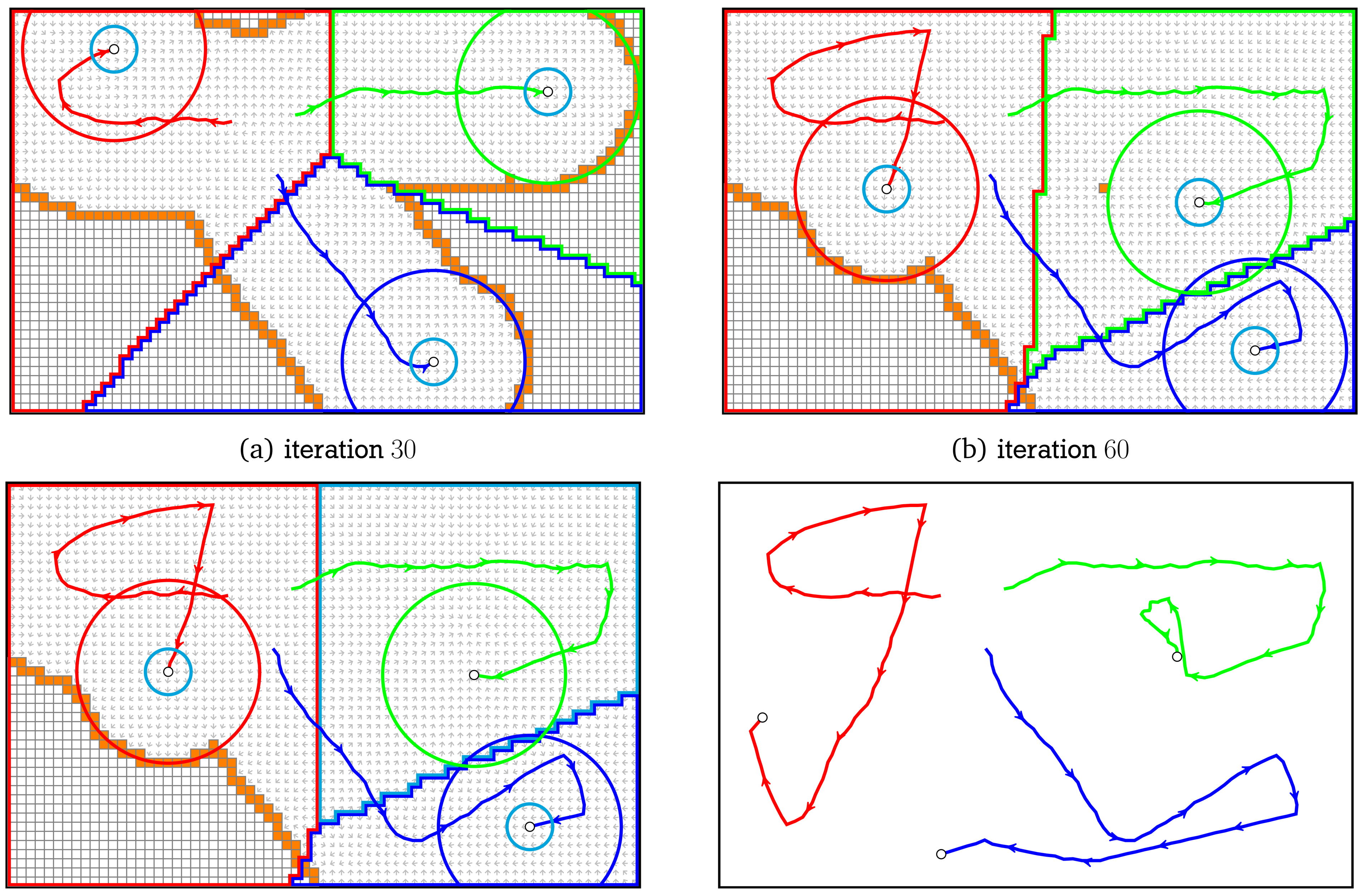
DisCoverage Simulator

- explore convex environment $\mathcal{Q}$ with $N = 3$ robots
- integration range $\overline{r} = 0.5\,\mathrm{m}$
- sensing range $r = 2.0\,\mathrm{m}$
- exploration task complete after 95 iterations
- detailed visualization of the progress below

Conclusion

DisCoverage is a novel approach to multi-robot exploration merging the choice of target points and path planning into a single step. Based on a Voronoi partition, each robot optimizes a locally computable objective function to automatically obtain control vectors which assure simultaneous exploration of different regions of uncharted territory. This is achieved by introducing a density function ϕ as a function of the time-varying frontier $\partial\mathcal{S}$. In line with the solution to the coverage problem, DisCoverage is provably correct. Hence, exploration of the entire environment is always guaranteed.

Detailed Results of the Multi-Robot Exploration Process



(a) iteration 30
(b) iteration 60
(c) iteration 61
(d) iteration 95

References

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