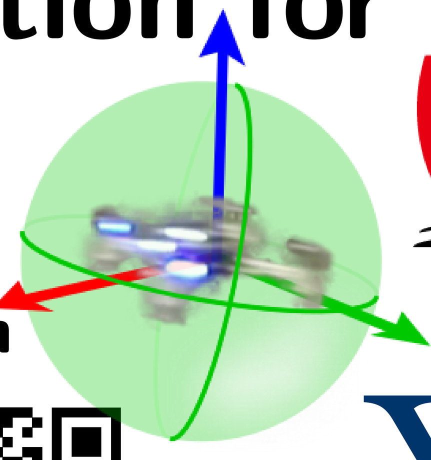
Energy-Aware Ergodic Search: Continuous Exploration for Multi-Agent Systems with Battery Constraints



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`github.com/adamseew/enerergo`

Code **Preprint**

Context

Ergodic search is a method to derive robots' trajectories that visit areas with high information density while quickly passing areas with low information density [1, 2]. The user specifies areas of interest, e.g., where the robots should spend more time exploring in a search and rescue scenario [3], where the robots should collect more data in a precision agriculture scenario [4], etc.

Recent efforts include swarm control, manipulation, and tactile sensing, among others. However, existing literature does not consider the robot's energy constraints, limiting how long a robot can explore. In fact, if the robots are battery-powered, it is physically not possible to continuously explore on a single battery charge.

Our work tackles this challenge, answering if it *is possible to tradeoff battery and coverage so that there is one agent exploring at all times.*

Methods: Ergodic search

The goal of ergodic search is to minimize an ergodic metric

$$\mathcal{E}(\boldsymbol{\delta}, \mathbf{q}(t)) := \frac{1}{2}\sum_{k\in\mathcal{K}} \Lambda_k \big(c_k(\mathbf{q}(t)) - \phi_k(\boldsymbol{\delta})\big)^2, \quad (1)$$

where ϕ_k are coefficients derived with Fourier series on a spatial distribution ϕ and c_k on the trajectory $\mathbf{q}(t)$ and Λ_k is a weight factor. If ${}^k\mathbf{u}(t)$, ${}^k\mathbf{q}(t)$ is each robot's control and state, the ergodic metric is now evaluated for multiple agents

$$\mathcal{E}(\boldsymbol{\delta},\boldsymbol{\Theta}_{\mathbf{q}}) := \tfrac{1}{2}\textstyle\sum_{k\in\mathcal{K}} \Lambda_k \Big(\frac{1}{n}\sum_{j\in[n]} c_k({}^j\mathbf{q}(t)) - \phi_k(\boldsymbol{\delta})\Big)^2, \quad (2)$$

where the term $\boldsymbol{\Theta}_{\mathbf{q}}$ is ${}^1\mathbf{q}(t), {}^2\mathbf{q}(t), \dots, {}^n\mathbf{q}(t)$, and $\boldsymbol{\Theta}$ is $\boldsymbol{\Theta}_{\mathbf{q}}, {}^1\mathbf{u}(t), {}^2\mathbf{u}(t), \dots {}^n\mathbf{u}(t)$. $\mathcal{T}_k$ is $[{}^kt_0, {}^kt_f]$.

Methods: Battery modeling

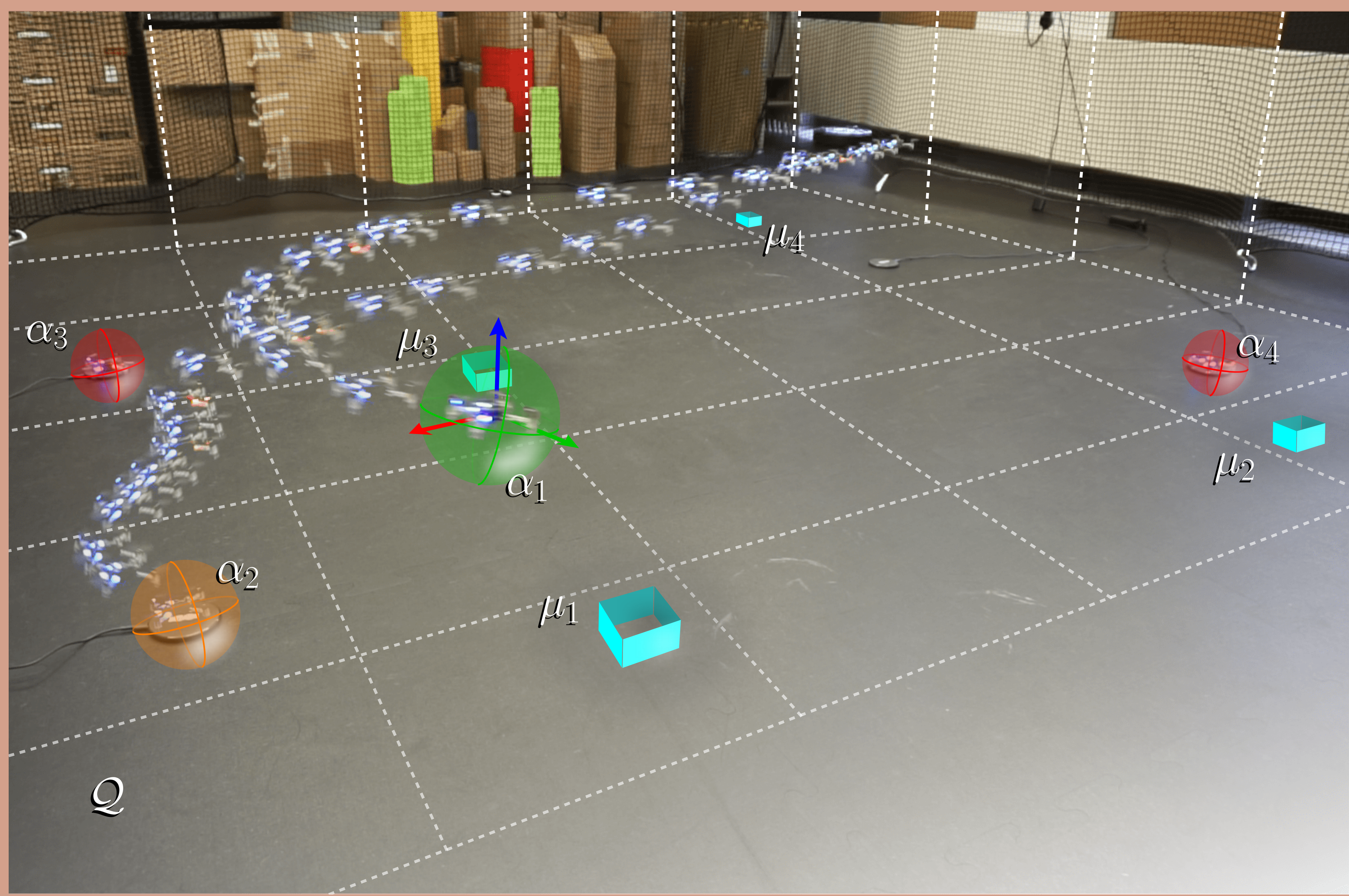
To derive a battery model for continuous exploration let us consider an abstract equivalent circuit model [5, 6] ${}^k\mathbf{b}$ per each agent k.
In order to satisfy the battery state of charge (SoC) and always keep at least one agent exploring, ergodic search must satisfy additionally

$$\exists k \in [n] \text{ s.t. } {}^k\mathbf{b}_{\mathsf{SoC}}(t_f) \in (0, b_f], \quad (3)$$

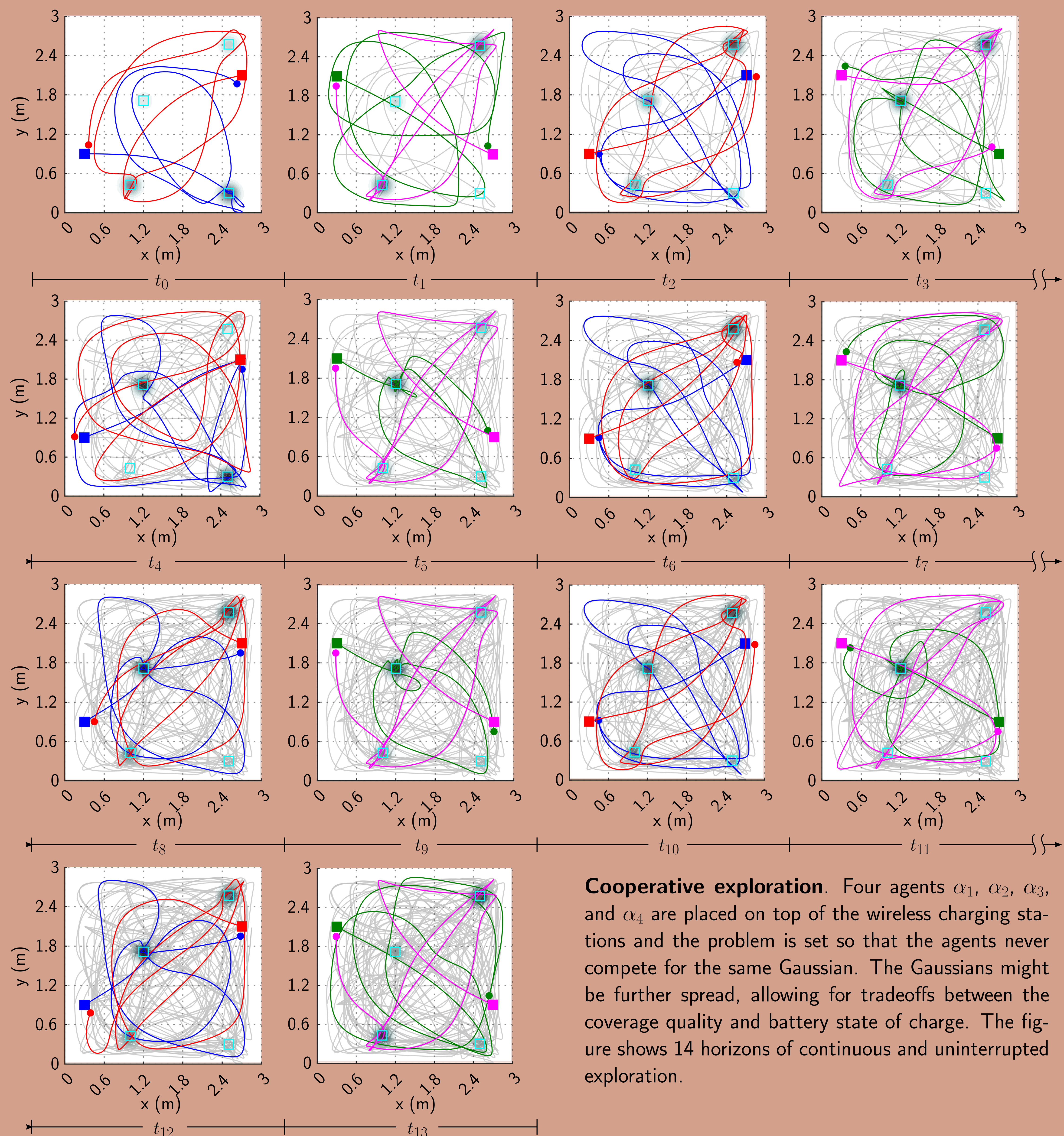
where $b_f \in (0, 1] \subset \mathbb{R}_{>0}$ is a given desired battery SoC at the final time instant derived via the battery model ${}^k\mathbf{b}_{\mathsf{SoC}} \in {}^k\mathbf{b}$.

Results: Uninterrupted exploration

Our experiments are implemented in simulation, and physical experiments are implemented in Python and conducted using Crazyflie 2.0 robots positioned on top of wireless charging stations. We achieve continuous, uninterrupted exploration with at least one agent exploring at all times.



Example of energy-aware ergodic search. A set of agents explores $\mathcal{Q}$, focusing on areas with high information density μ_1, μ_2, μ_3, and μ_4, employing ergodic search. The exploration is continuous and uninterrupted so that there is always one agent exploring – α_1, whereas α_2, α_3, and α_4 are recharging. The colors of the spheres indicate the state of charge.



Cooperative exploration. Four agents α_1, α_2, α_3, and α_4 are placed on top of the wireless charging stations and the problem is set so that the agents never compete for the same Gaussian. The Gaussians might be further spread, allowing for tradeoffs between the coverage quality and battery state of charge. The figure shows 14 horizons of continuous and uninterrupted exploration.

References

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