Coverage Hole Prevention for Environmental Monitoring with Quadcopters

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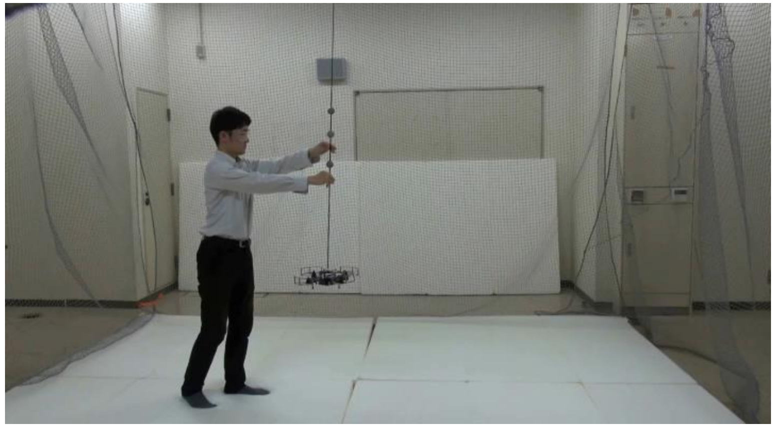
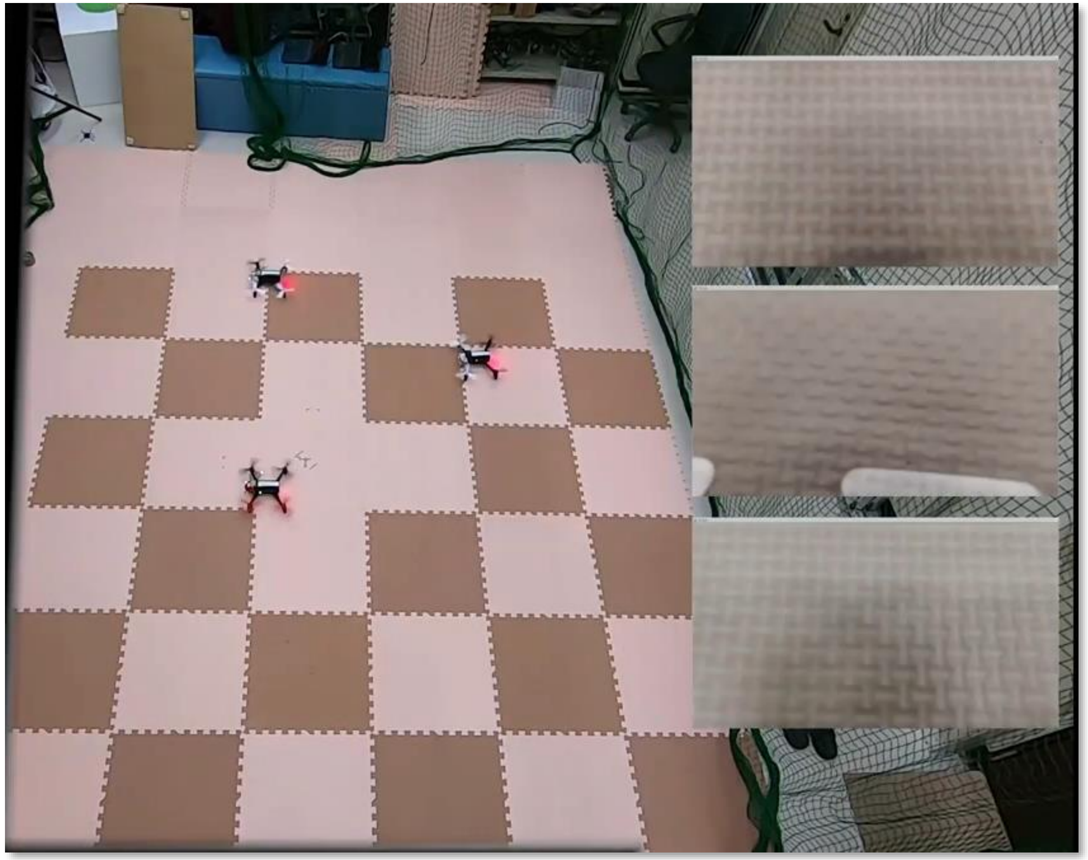
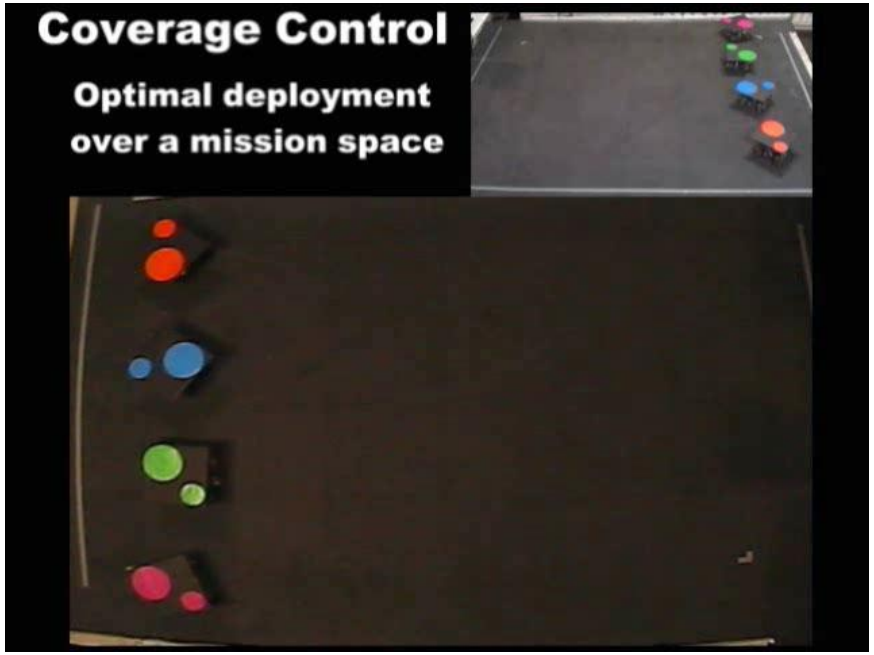
Visual Monitoring & Quadcopters



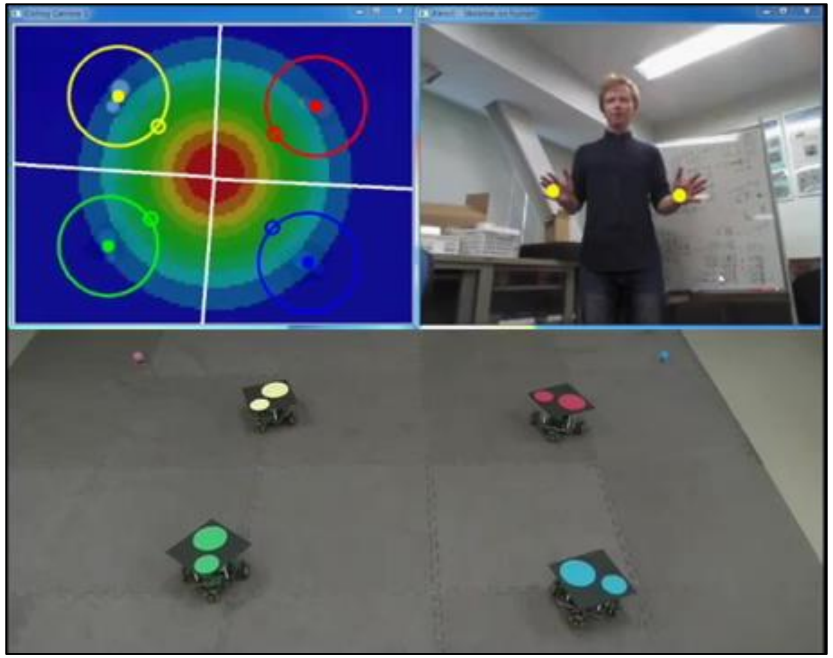


How to monitor an environment while avoiding overlooks of events/objects by a team of quadcopters

Coverage Control



Coverage control with uniform density



Coverage control with a human specified density

Deploy mobile sensors to optimally collect the data

[1] J Cortes, S Martinez, T Karatas, F Bullo, Coverage control for mobile sensing networks,
IEEE Trans. Robotics and Automation vol. 20, no 2, pp. 243-255, 2004

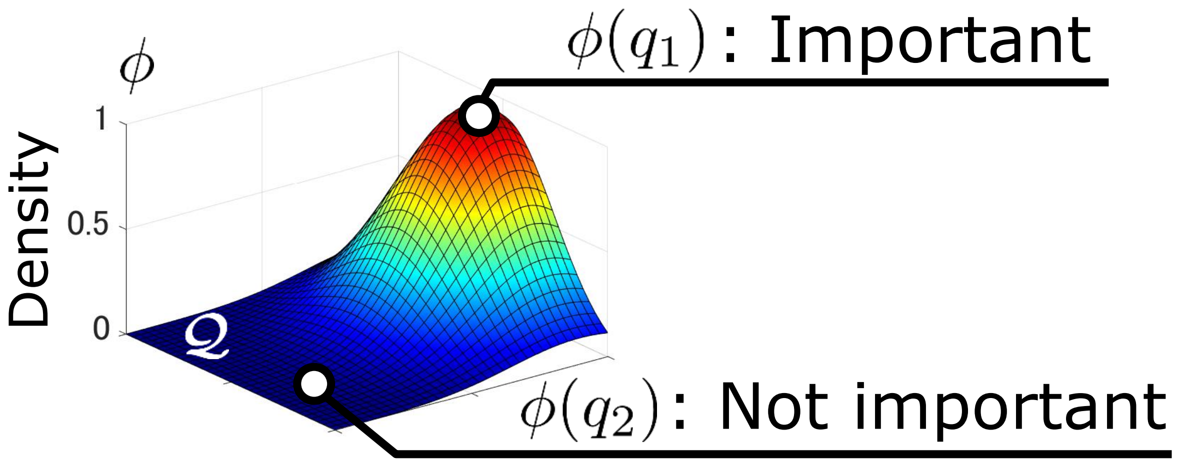
Applications to drones

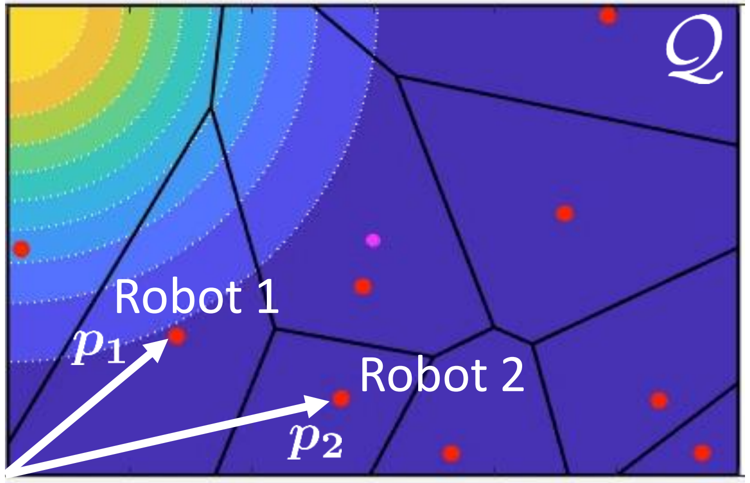
[2] M. Schwager, B. J. Julian, M. Angermann, and D. Rus, Eyes in the Sky: Decentralized Control for the Deployment of
Robotic Camera Networks, Proc. the IEEE, vol. 99, no. 9, pp. 1541–1561, 2011.

Coverage Control

Robot Dynamics: $\dot{p}_i = u_i$

Density Function: ϕ





●: Robot

Coverage Performance

Point importance

$$J(p) = -\int_{q\in\mathcal{Q}} \min_i \|q - p_i\|^2 \phi(q) dq$$

Sensing Performance

Gradient method

Control Input

$$u_{i,cov} = \left(\frac{\partial J}{\partial p_i}\right)(p)$$

[1] J Cortes, S Martinez, T Karatas, and F Bullo, Coverage control for mobile sensing networks, IEEE Trans. Robotics and Automation, vol. 20, no. 2, pp. 243-255, 2004

Coverage Control

Control input

$$u_{i,cov} = \left(\frac{\partial J}{\partial p_i}\right)(p) = M_i(p)(C_i(p) - q_i)$$

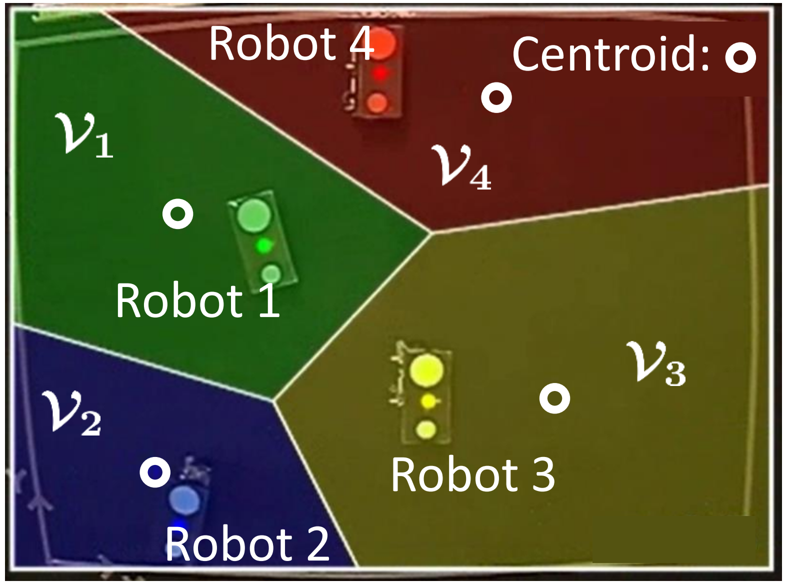
The standard Voronoi partition

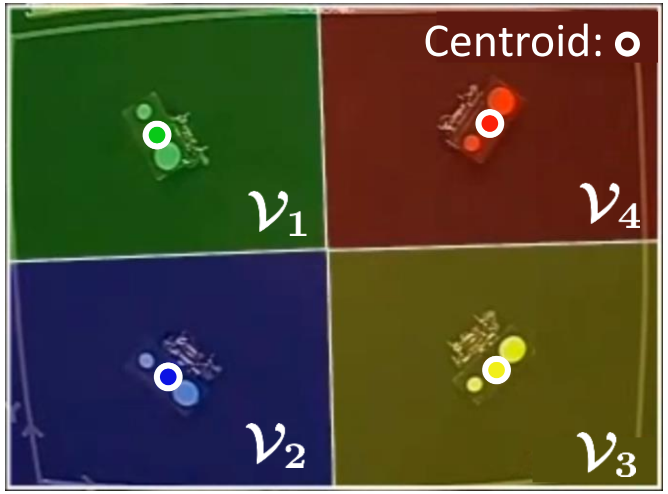
$$\mathcal{V}_i(p) = \{q \in \mathcal{Q} \mid \|q - p_i\| \le \|q - p_j\| \quad \forall j \neq i\}$$

Euclidean distance

$M_i(p)$: Area of Voronoi region

$C_i(p)$: Centroid of Voronoi region





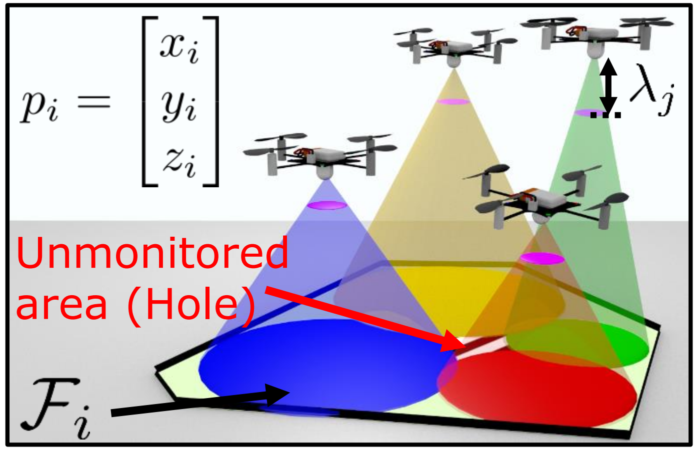
Robot i converges to a centroid of its Voronoi region $\mathcal{V}_i(p)$.

Coverage control can be applied to drone network.

➡ What are the differences?

[1] J Cortes, S Martinez, T Karatas, and F Bullo, Coverage control for mobile sensing networks, IEEE Trans. Robotics and Automation vol. 20, no. 2, pp. 243-255, 2004

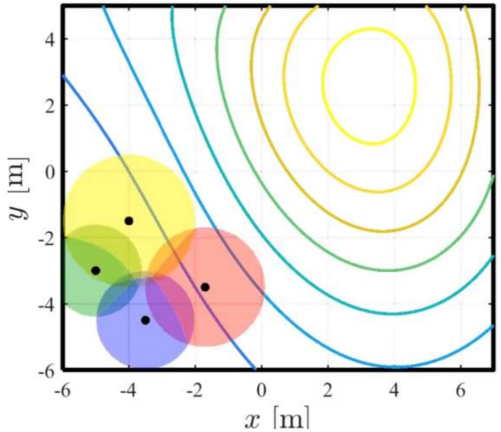
Coverage Control with Visual Sensor & Quadcopter



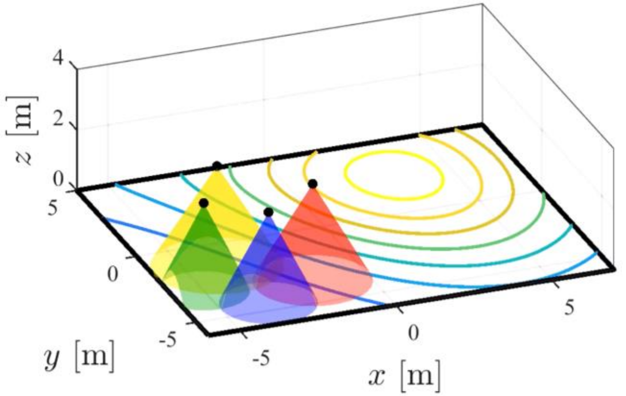
Control variables

$$\mathbf{p}_i = [p_i^T \quad \lambda_i]^T$$

$\mathcal{F}_i$: i's field of view (FOV) (circular shape)



Top View



Side View

With limited field of view, the unmonitored area may appear in–between the team.

Avoid overlooking of targets appearing small from the sky

Cover the important area completely not to miss events

➡

Prevent the appearance of coverage holes

while maximizes the monitoring performance via the coverage control.

Coverage hole: the generalized Voronoi diagram

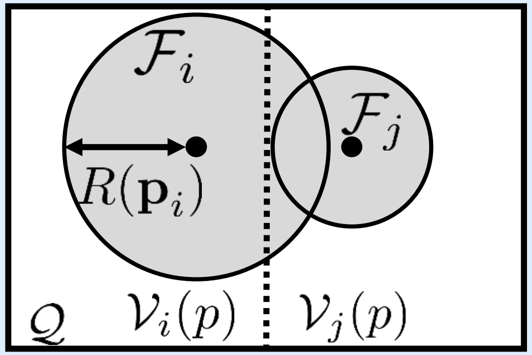
Power diagram [3]

A generalized Voronoi diagram accounting heterogeneity of a sensing radius

$$\mathcal{V}_i(p) = \{q \in \mathcal{Q} \mid d_{\mathcal{P}}(\mathbf{p}_i, q) \leq d_{\mathcal{P}}(\mathbf{p}_j, q) \quad \forall j \neq i\}$$

$$d_{\mathcal{P}}(\mathbf{p}_i, q) = \|[q_x \ q_y]^T - [x_i \ y_i]^T\|^2 - R(\mathbf{p}_i)^2$$

Horizontal distance from Robot i — Sensing radius of Robot i

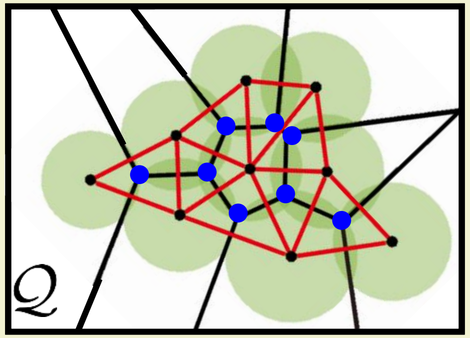


Power diagram

Preventing coverage holes among a team

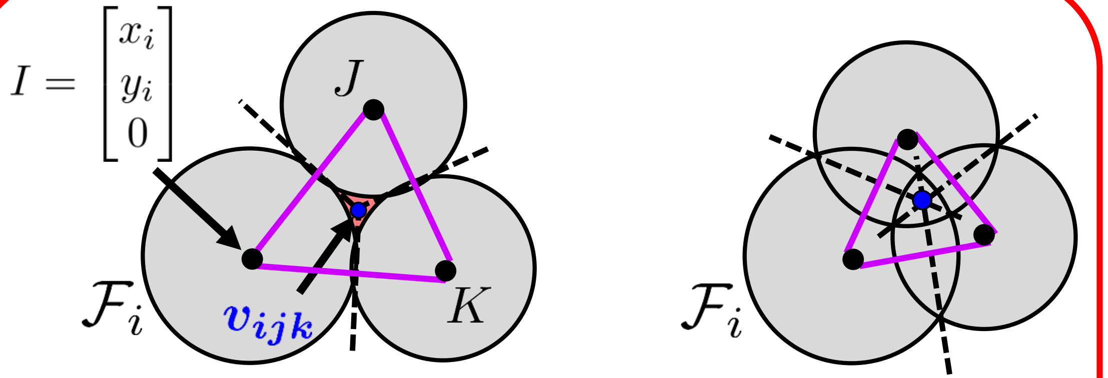
Each drone should confine Vonoronoi vertices of its cell, created by the trio determined by the triangular subgraphs, in its FOV.

→ Divide the problem into each triangular subgraph



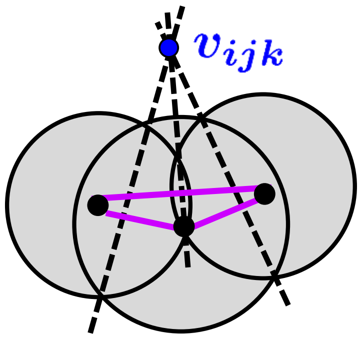
[3] F. Aurenhammer, Power Diagrams: Properties, Algorithms and Applications, SIAM Journal on Computing, vol. 16, no. 1, pp. 78-96, 1987.

Conditions to prevent a hole in-between trio



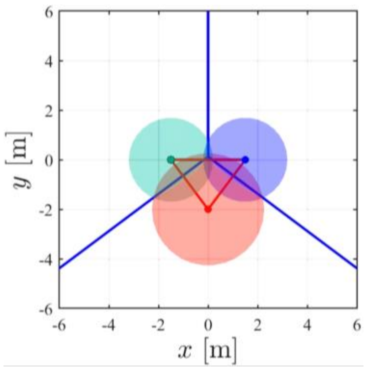
$\boldsymbol{v_{ijk}}$ is contained in i's field of view $\mathcal{F}_i$

OR

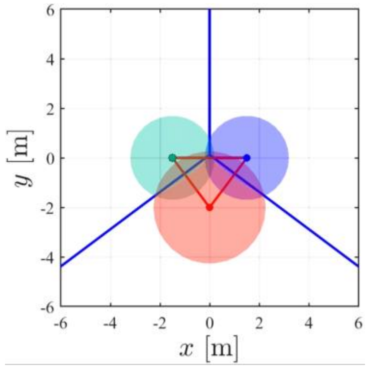


$\boldsymbol{v_{ijk}}$ is Not inside of $\triangle IJK$

$(v_{ijk} \in \mathcal{F}_i) \vee (v_{ijk} \notin \triangle IJK)$ **is the necessary and sufficient condition not to make a hole among trio.**



Only $(v_{ijk} \in \mathcal{F}_i)$

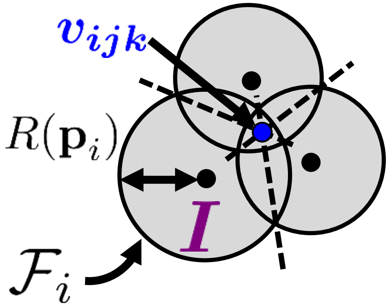


$(v_{ijk} \in \mathcal{F}_i) \vee (v_{ijk} \notin \triangle IJK)$

[4] R. Funada, M. Santos, R. Maniwa, J. Yamauchi, M. Fujita, M. Sampei, and M. Egerstedt, Distributed Coverage Hole Prevention for Visual Environmental Monitoring With Quadcopters Via Nonsmooth Control Barrier Functions, IEEE Transactions on Robotics, vol. 40, pp. 1546-1565, 2024.

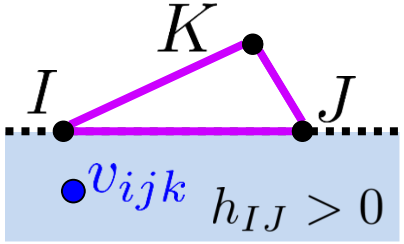
Conditions not to make a hole

Explicit form of the set $(v_{ijk} \in \mathcal{F}_i) \vee (v_{ijk} \notin \triangle IJK)$



$$v_{ijk} \in \mathcal{F}_i \quad = \quad h_{i,\mathcal{F}} = R(\mathbf{p}_i)^2 - \left\| v_{ijk} - \begin{bmatrix} x_i & y_i & 0 \end{bmatrix}^T \right\|^2 > 0$$

$R(\mathbf{p}_i)$: The radius of i 's field of view $\mathcal{F}_i$



$$v_{ijk} \notin \triangle IJK \quad = \quad (h_{IJ} > 0) \vee (h_{JK} > 0) \vee (h_{KI} > 0)$$

$h_{IJ} > 0$ when v_{ijk} and $\triangle IJK$ are in the different half plane

$$(v_{ijk} \in \mathcal{F}_i) \vee (v_{ijk} \notin \triangle IJK) \quad = \quad h_{i,\triangle IJK} = \max\{h_{i,\mathcal{F}}, h_{IJ}, h_{JK}, h_{KI}\} > 0$$

How to integrate this constraint to the coverage control?

[4] R. Funada, M. Santos, R. Maniwa, J. Yamauchi, M. Fujita, M. Sampei, and M. Egerstedt, Distributed Coverage Hole Prevention for Visual Environmental Monitoring With Quadcopters Via Nonsmooth Control Barrier Functions, IEEE Transactions on Robotics, vol. 40, pp. 1546-1565, 2024.

Control Barrier Function (CBF)

System dynamics

$$\dot{\mathbf{p}} = f(\mathbf{p}) + g(\mathbf{p})u$$

Admissible set

$$\mathcal{C} = \{\mathbf{p} \mid h(\mathbf{p}) \geq 0\} \qquad \mathbf{p}(t) \in \mathcal{C},\ \forall t \geq t_0$$

Control Barrier Function (CBF)

For all $x \in \mathcal{C}$, there exists $u \in \mathbb{R}^m$ such that:

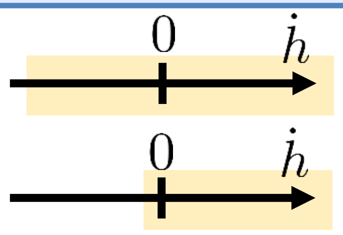
$$\underbrace{\frac{\partial h}{\partial \mathbf{p}}(\mathbf{p})\left(f(\mathbf{p}) + g(\mathbf{p})u\right)}_{\dot{h}(\mathbf{p},u)} \geq -\alpha(h(\mathbf{p}))$$

Extended class $\mathcal{K}$ function

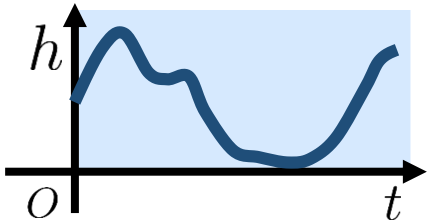
$\dot{h} \geq -\alpha(h)$

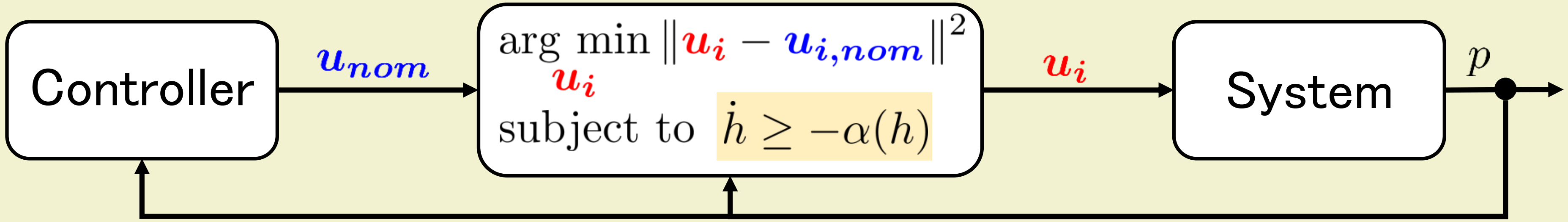
$h \gg 0$

$h \approx 0$



h may decay, but remains $h \geq 0$





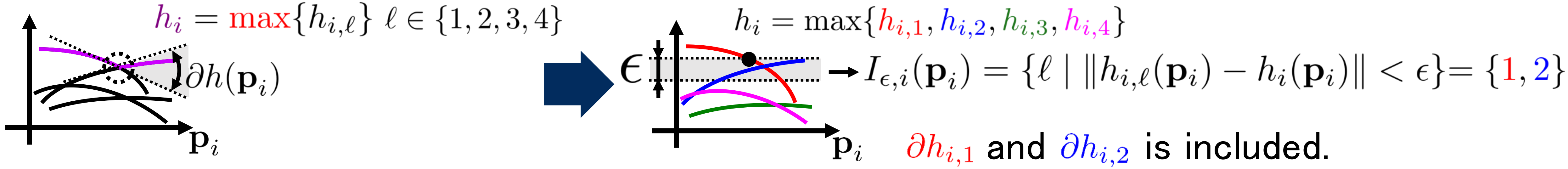
[5] A. D. Ames, J. W. Grizzle and P. Tabuada, Control barrier function based quadratic programs with application to adaptive cruise control, CDC, pp. 6271-6278, 2014.

CBF & Quadratic Programming(QP)-based Controller

CBF preventing coverage hole

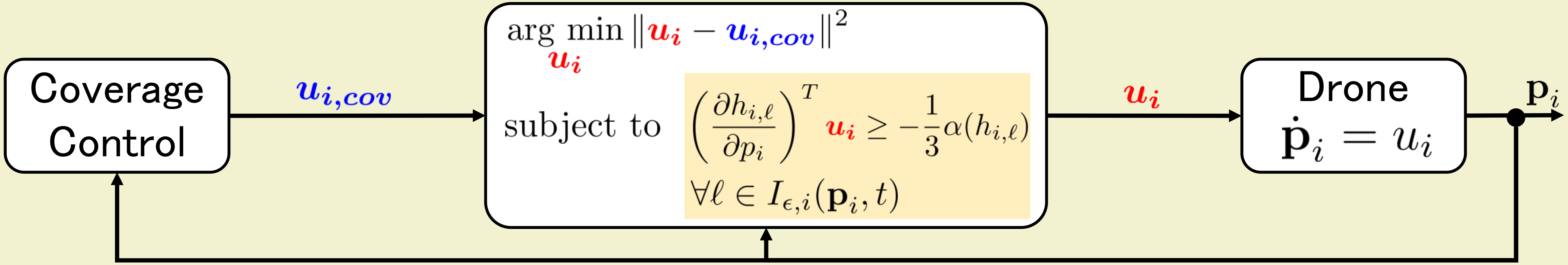
$(v_{ijk} \in \mathcal{F}_i) \vee (v_{ijk} \notin \triangle IJK)$ ➡ $h_{i,\triangle IJK} = \max\{h_{i,\mathcal{F}}, h_{IJ}, h_{JK}, h_{KI}\} > 0$

Near a nonsmooth point $\mathbf{p}_i$, gradients composing $\partial h(\mathbf{p}_i)$ need to be included [6].



QP-based controller

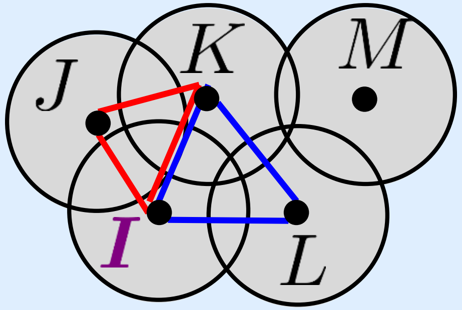
QP can be distributed (though conservative) using the symmetric nature of $h_{i,\ell}$, $h_{j,\ell}$ and $h_{k,\ell}$, $\forall \ell \in \{1,2,3,4\}$.



[6] P. Glotfelter, J. Cortés and M. Egerstedt, Boolean Composability of Constraints and Control Synthesis for Multi-Robot Systems via Nonsmooth Control Barrier Functions, CCTA, pp. 897-902, 2018.

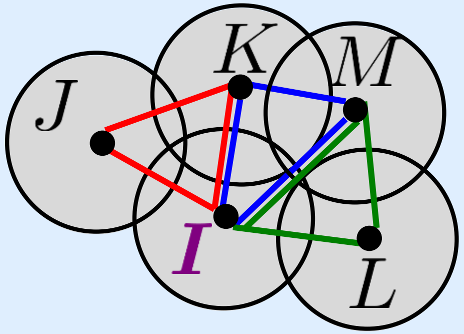
Switching of the graph & CBF

Graph change can cause addition/subtraction of CBF to be considered [7].



$(h_{i,\triangle IJK} > 0) \wedge (h_{i,\triangle IKL} > 0)$

Graph Change



$(h_{i,\triangle IJK} > 0) \wedge (h_{i,\triangle IKL} > 0) \wedge (h_{i,\triangle IML} > 0)$

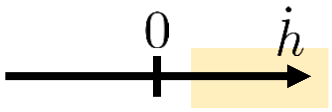
Addition

If the graph change does not cause sudden appearances of a hole, it is not a problem.

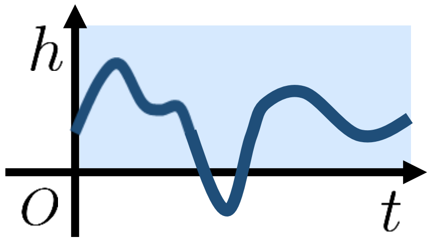
But... Some types of graph changes could generate a hole.

Even if $h < 0$ due to graph changes, CBF can eliminate a hole.

$\dot{h} \geq -\alpha(h)$ $\boldsymbol{h < 0}$



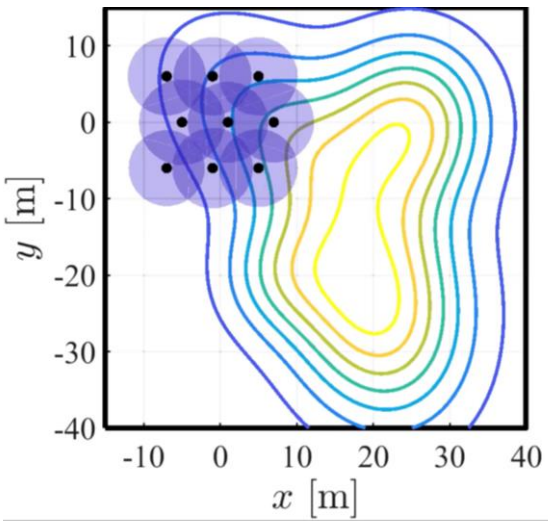
CBF can drive $\boldsymbol{h}$ back to $\boldsymbol{h \geq 0}$



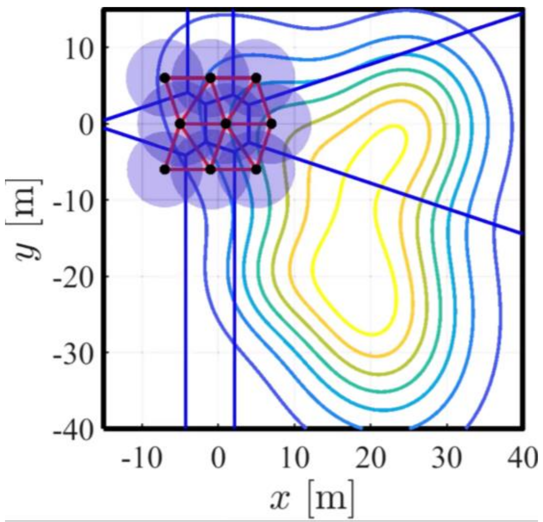
Check in simulation

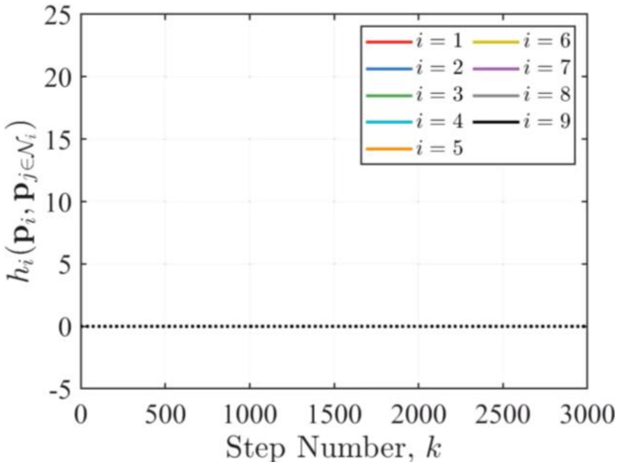
[7] P. Glotfelter, I. Buckley, and M. Egerstedt, Hybrid Nonsmooth Barrier Functions With Applications to Provably Safe and Composable Collision Avoidance for Robotic Systems, RA-L, pp. 1303-1310, 2019.

Simulation

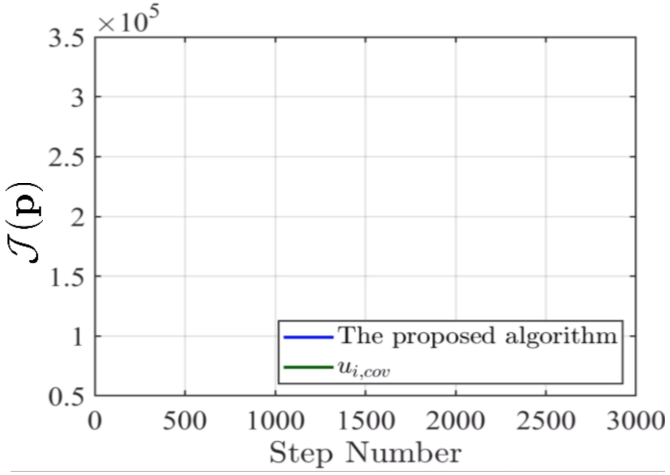


Coverage control $u_{i,\mathrm{cov}}$
(without CBF)





The proposed method and h_i (CBF)



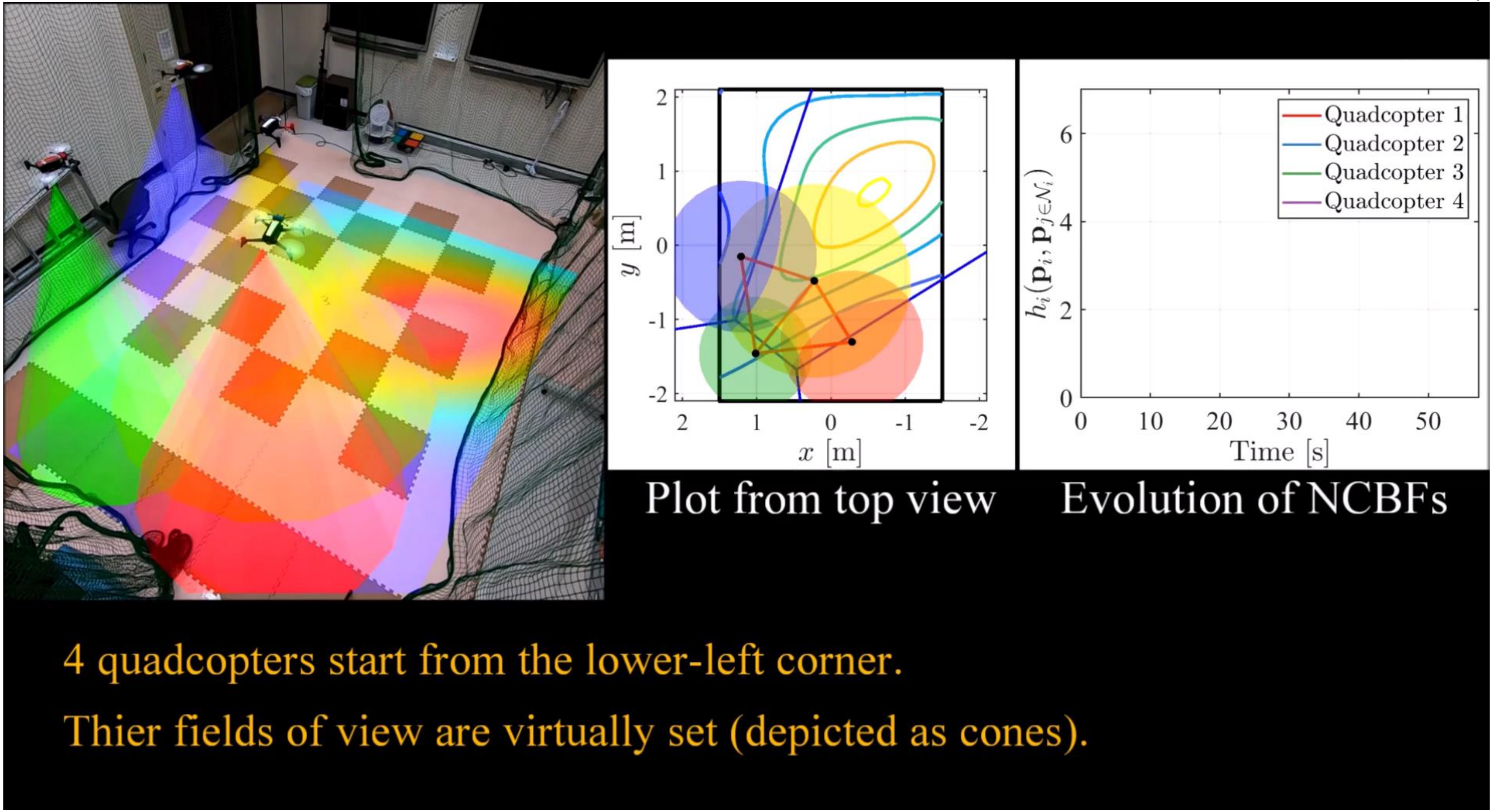
Coverage Performance

The proposed method prevents holes, while achieving the same coverage performance $u_{i,\mathrm{cov}}$.

$h > 0$, hence the prevention of coverage holes, is achieved except for $k \simeq 750$.

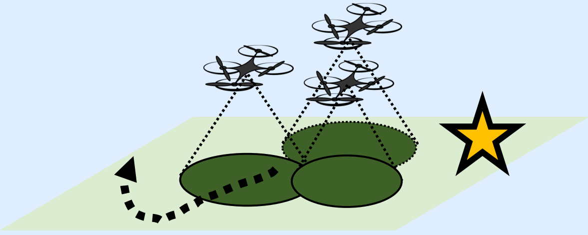
At $k \simeq 750$, a graph change causes the sudden appearance of a hole,
but the proposed algorithm successfully eliminates it.

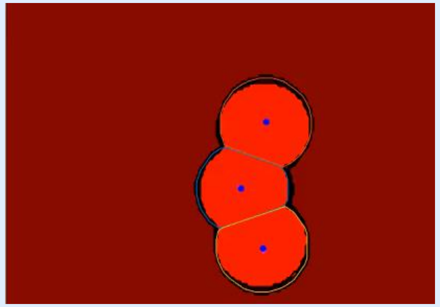
Experiment 1: Coverage Hole Prevention Only



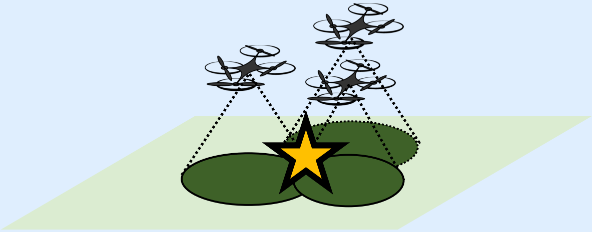
Experiment 2: Object Search Scenario

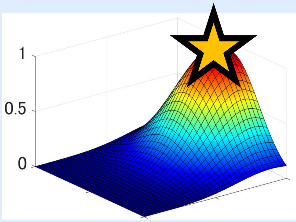
Task Specification via Coverage Control and Visual Feedback





Detect



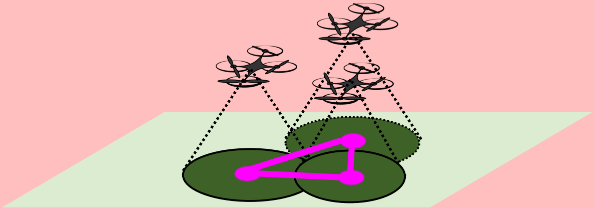


Patrol via Time-decaying density [8]

Stay by setting high importance

Constraint via Control Barrier Function

+



Switch

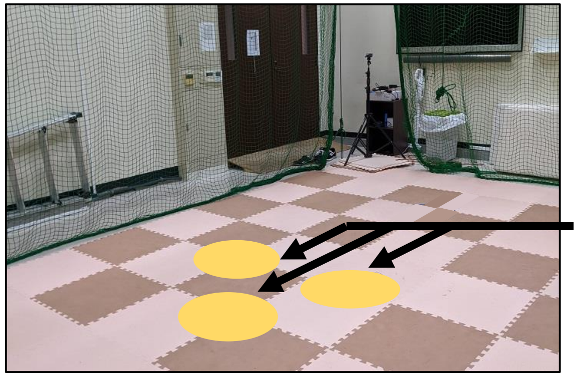
Prevent coverage hole

Flight time limit [9]

Control input & Constraints are switched depending on the situation.

[8] K. Sugimoto, T. Hatanaka, M. Fujita and N. Huebel, Experimental study on persistent coverage control with information decay, SICE AC, pp. 164-169, 2015.
[9] G. Notomista, S. F. Ruf and M. Egerstedt, Persistification of Robotic Tasks Using Control Barrier Functions, RA-L, vol. 3, no. 2, pp. 758-763, 2018.

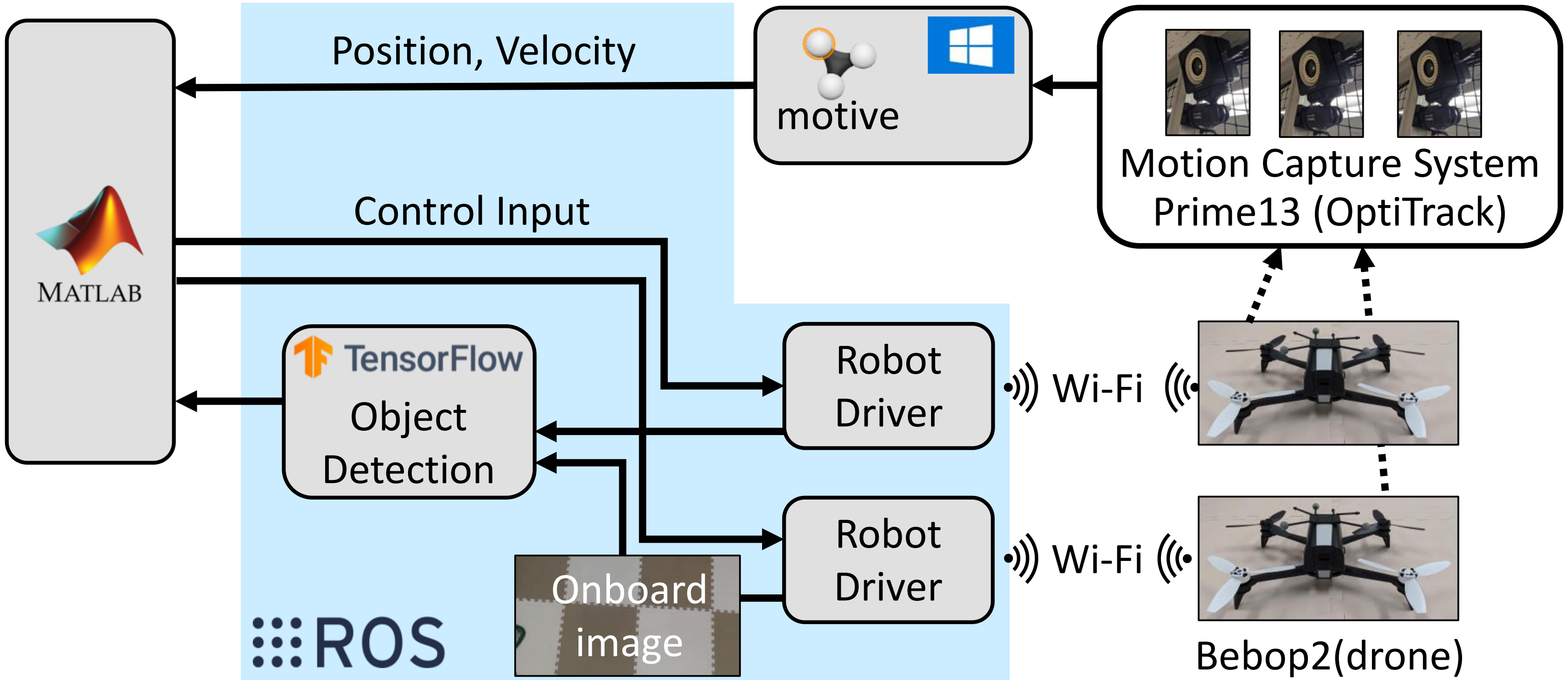
Experimental setting

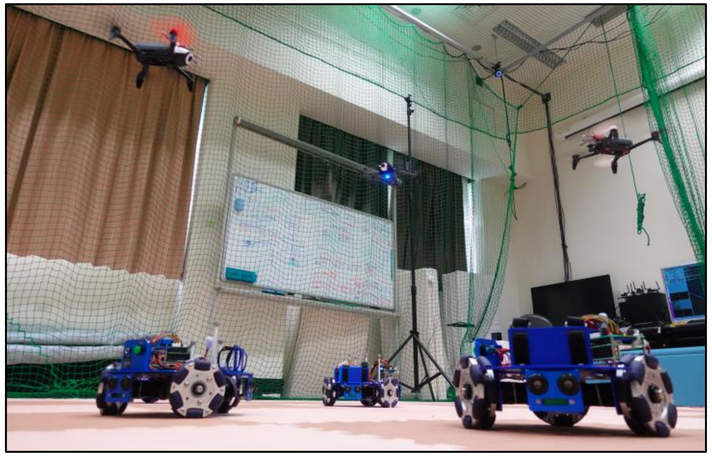


Field
2.2 × 3.2m

Virtual
Charging Stations

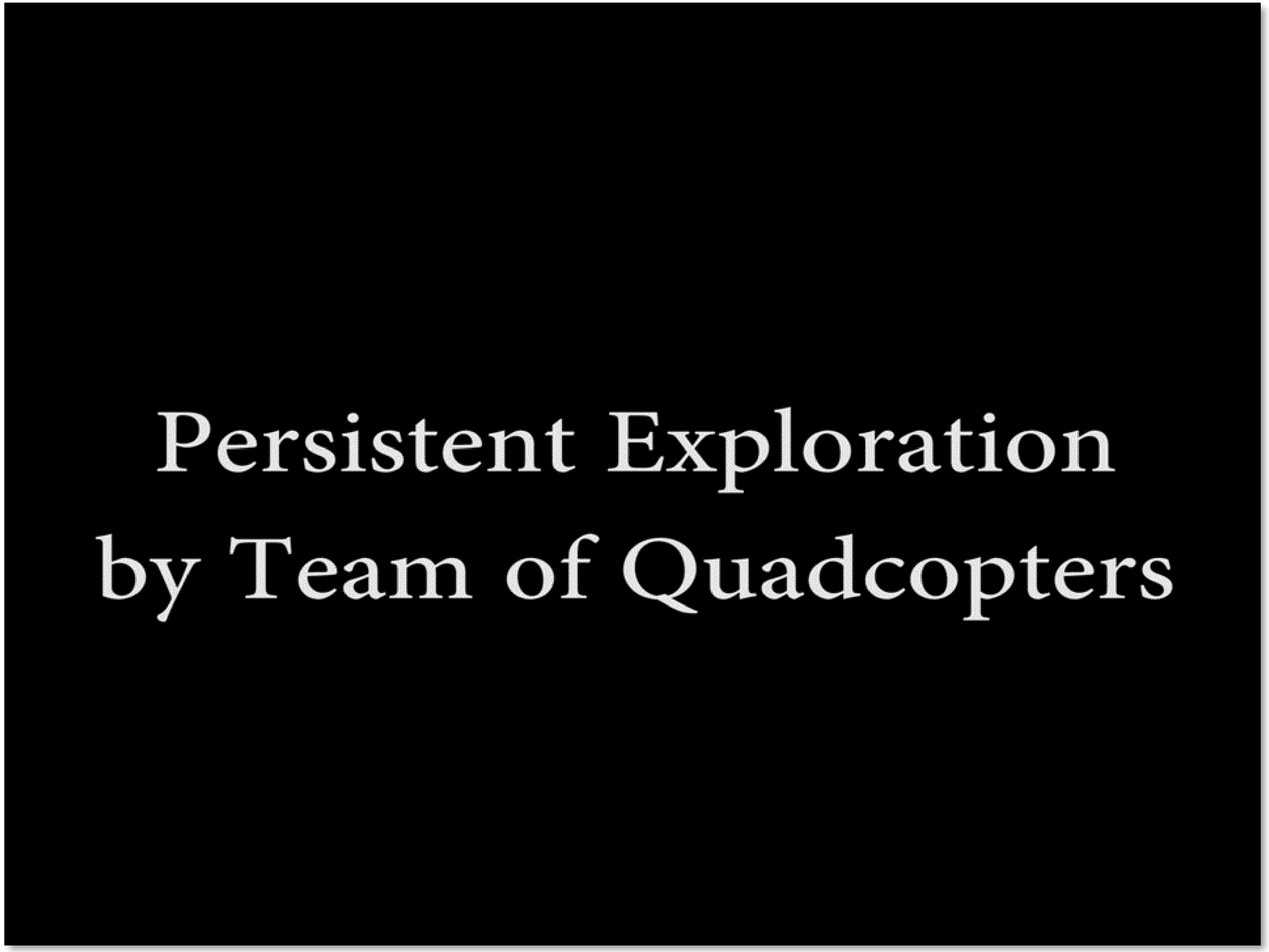
Target Object





Tokyo Tech Robot Zoo Sky

Experiment result with visual feedback

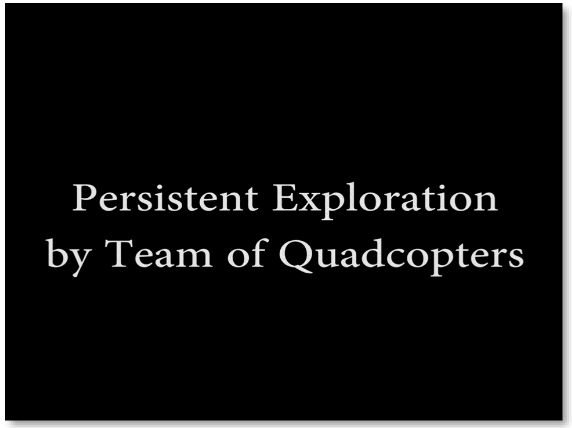


[10] J. Yamauchi, T. Gencho, R. Funada, T. Hatanaka, and M. Fujita, Persistent Visual Coverage Control Ensuring Field of Views' Overlap with Information Reliability and Energy Management, IEEJ Trans. Electronics, Information and Systems, vol. 141, no. 3, pp. 417-425, 2021. (Written in Japanese)

Conclusion and Future works

Conclusion

- ✓ We propose the visual monitoring method that prevents the appearance of coverage holes.
- ✓ Visual feedback is integrated in the object-search scenario.



Future works

- ☐ Evaluation utilizing a virtual environment.
- ☐ Outdoor experiment and implementation in the real application scenario.