

# **Flexible Resilient Autonomous Systems**

**(FA9550-18-1-0097)**

**PI: Katia Sycara (Carnegie Mellon University)**

**Co-PI: Michal Pechoucek (Czech Technical University in Prague)**

**Senior Personnel: Dr. Lukas Chrupa**

**AFOSR Program Review:**  
**Computational Cognition and Machine Intelligence Program**  
**(October 6, 2020)**



# Flexible and Resilient Autonomous Systems

## (Katia Sycara, Michal Pechoucek)

### **Research Objectives:**

- Develop multi-agent planning and network aware coordination in a dynamic, partially observable adversarial environment with the goal to provide theoretical foundations for building Flexible and Resilient Autonomous Systems

### **Technical Approach:**

- Probabilistic planning and offline policy generation
- Distributed coordination
- Game-theoretic models

### **Key Scientific Contributions:**

- Distributed multi-agent resilient coordination
- Game theory and game playing models for strategic reasoning
- Learning in an adversarial environment

### **DoD Benefits:**

- Provide advanced decision support capabilities for human operators and decision makers
- Improve system resiliency and mission success by actively adapting strategies and tactics based on the observed enemy and environment response

## List of Project Goals

1. Deterministic/nondeterministic multi-agent fault-tolerant planning
2. Multi-agent resilient coordination
3. Learning the environment via distributed multi-agent sensing
4. Online strategic decision making with machine learning for heuristics and models of the opponent
5. Improve scalability with abstraction and online strategic decision making

## Progress Towards Goals (or New Goals)

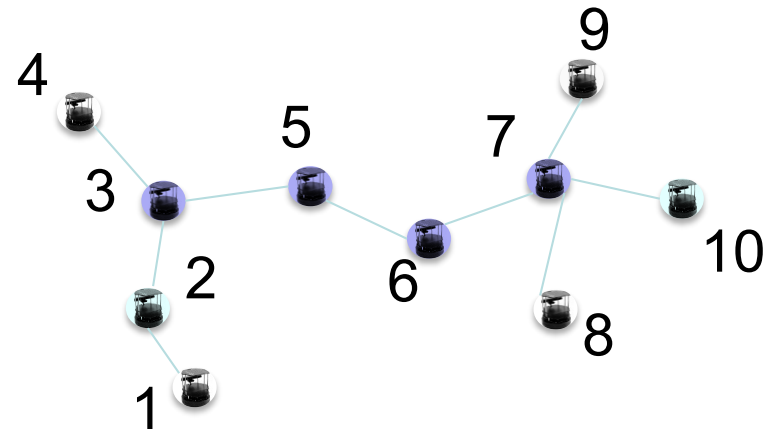
Developed methods for :

- Resilient communication and coordination (maintaining  $k$ -connectivity)
- Energy efficient coordination for persistent surveillance
- Multi-agent collaboration for environmental monitoring and adaptive sampling
- Coverage control with connectivity maintenance for robotic sensor networks.
- Planning and acting in dynamic environment in presence of non-deterministic exogenous events
  - Generating plans minimizing the number of consecutive "unsafe" action
  - Interleaving planning and acting such that unsafe states are crossed via robust plans
- Techniques for planning against a competitor in zero-sum games
  - Encoding the best response problem (from the Double Oracle
  - Developing heuristics for selecting and ordering critical actions prior to planning (improved scalability of previous approach)

# Multi-Robot Network Connectivity



Swarm Control via gesture [CMU MRSD Team Roborn 2014]



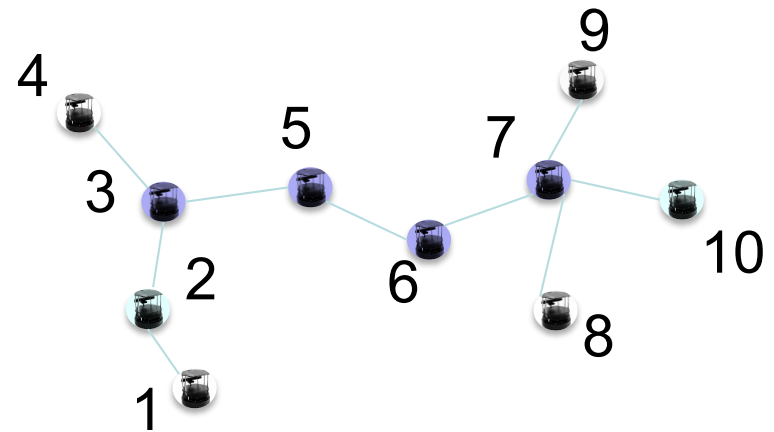
Multi-robot communication graph

- Local peer-to-peer interaction and information sharing in a *connected* multi-robot network to enable *collective* decision making or behaviors

# Multi-Robot Network Connectivity



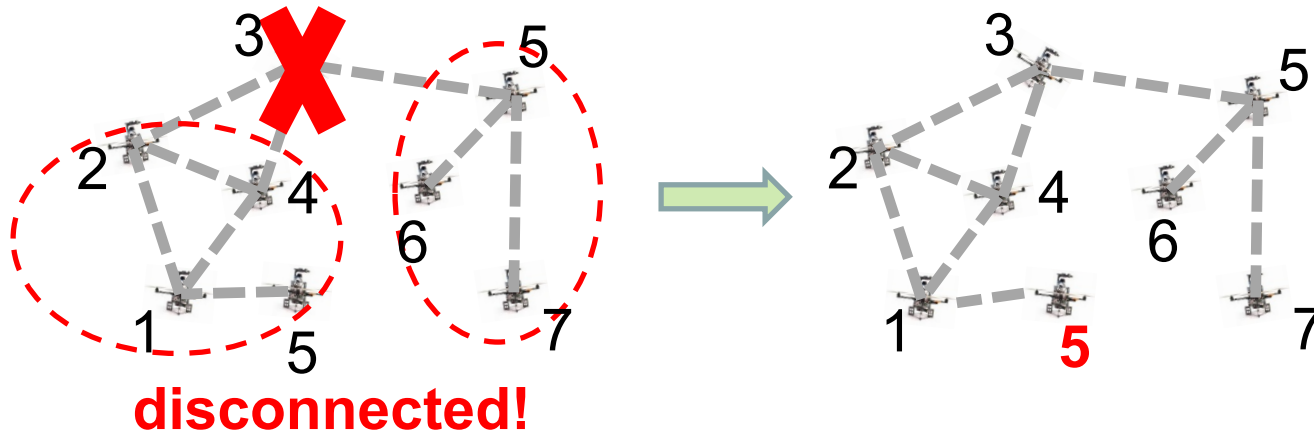
Swarm Control via gesture [CMU MRSD Team Roborn 2014]



Multi-robot communication graph

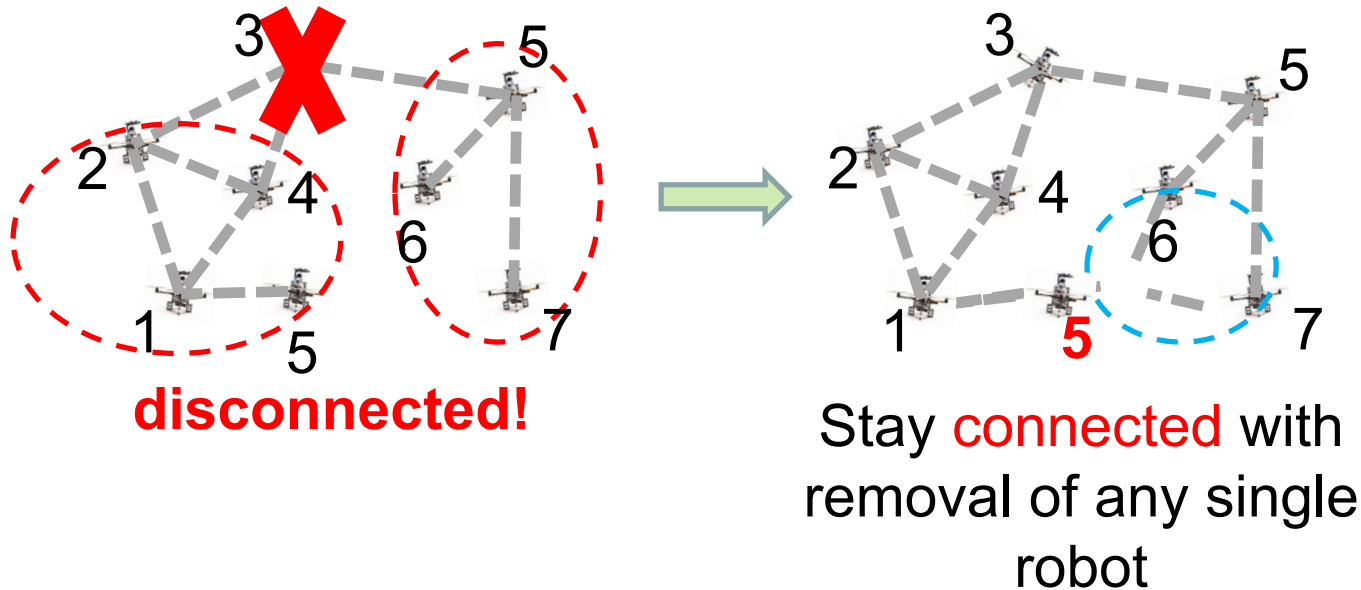
- Local peer-to-peer interaction and information sharing in a *connected* multi-robot network to enable *collective* decision making or behaviors
- Two robots are *connected* if they are located within each other's limited communication range

# Multi-Robot Connectivity *Maintenance*



**Failure of a single robot?**  
A strategy to increase connectivity for improved  
resilience of the network?  
Could disconnect the whole team!

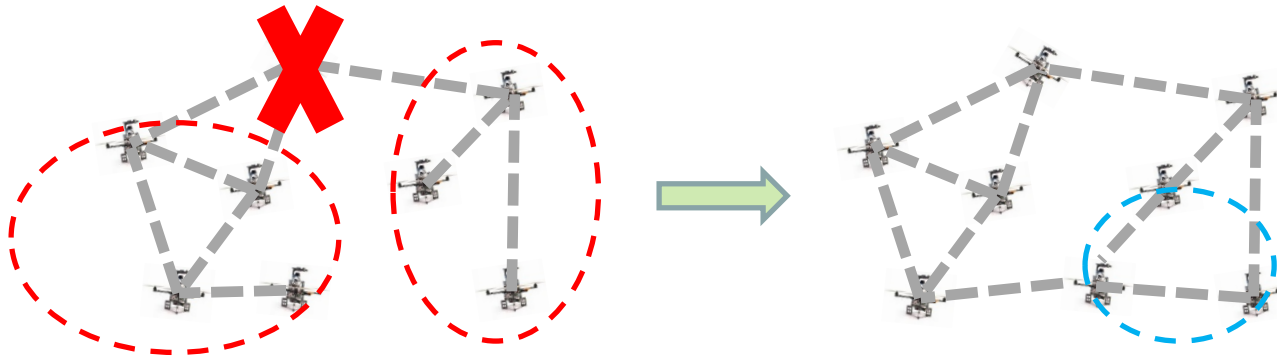
# Multi-Robot Connectivity *Maintenance*



A strategy to increase connectivity for improved resilience of the network?



# Multi-Robot $k$ -Connectivity *Enhancement*



**disconnected!**

Stay **connected** with  
removal of any single  
robot

**$k$ -connectivity [R. Diestel, 12]:** A connected graph  $G = (V, E)$  is said to be  $k$ -node connected (or  $k$ -connected) if it has more than  $k$  nodes and remains connected whenever fewer than  $k$  nodes are removed.

- Diestel, R., Graph theory, *Graduate texts in mathematics* 2012

# Resilient $k$ -Connectivity

Given pre-computed nominal multi-robot controllers for primary tasks, can we design a *resilient* connectivity *enhancement* algorithm to constrain the nominal controllers so that it:

- *formally* guarantees *any user-specified  $k$ -connectivity* of multi-robot network *without assuming* the network is initially  $k$ -connected
- *least constrains* the original task-related robot motions

Luo, W., Chakraborty, N., and Sycara, K., Minimally Disruptive Connectivity Enhancement for Resilient Multi-Robot Teams, (accepted to *IROS* 2020)

**Key Idea:** a *bilevel* optimization framework computing both optimal *k-connectivity topology* and *minimally modifying* a nominal task-related controller to preserve/form the computed topology

**Key Idea:** a *bilevel* optimization framework computing both optimal *k-connectivity topology* and *minimally modifying* a nominal task-related controller to preserve/form the computed topology

## Contribution:

- first work to formally guarantee a *k-connected multi-robot graph* *from any initial robots' positions and network connectivity*
- *resilient* to reduction in connectivity of multi-robot communication graph due to robot arrival and removal
- *minimal disruption* to primary tasks

# Minimally Disruptive Resilient Connectivity Framework

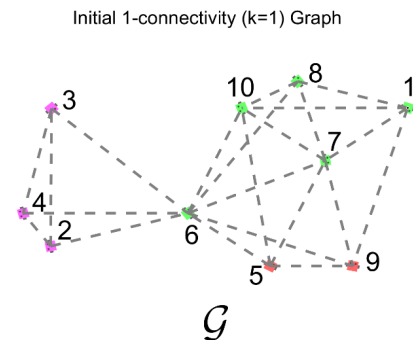
Connectivity Graph  
to construct

Original Task-prescribed  
Controller

$$\begin{aligned} \mathbf{u}^* &= \arg \min_{\mathcal{G}^c, \mathbf{u}} \sum_{i=1}^n \|u_i - \hat{u}_i\|^2 \\ \text{s.t. } \mathcal{G}^c &= (\mathcal{V}, \mathcal{E}^c) \text{ is } k\text{-connected} \\ \mathbf{u} &\in \mathcal{B}^s(\mathbf{x}) \cap \bigcap \mathcal{B}^c(\mathbf{x}, \mathcal{G}^c), \quad \|u_i\| \leq \alpha_i, \forall i = 1, \dots \end{aligned}$$

Collision-  
avoidance

Enhancing edges in  $k$ -connectivity graph –  
dynamic!



User specifies a desired connectivity  $k$

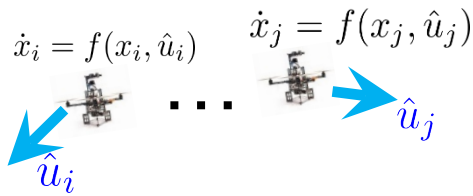
**Step 1 (define connectivity constraints):** Develop the optimal  $k$ -connectivity graph  $\mathcal{G}^c$  to invoke a set of pairwise connectivity constraints to enforce

**Step 2 (derive constrained controller):** minimally modified controller subject to collision-free and defined connectivity constraints using finite-time control barrier functions (FCBF) [A. Li et al. IROS18]

# ***k***-Connected Minimum Resilient Graph (***k***-CMRG)

**Step 1 (define connectivity constraints)** : A novel *k*-Connected Minimum Resilient Graph (*k*-CMRG) algorithm to find an *optimal k-connected graph*  $\mathcal{G}^{c*}$  to preserve/form that

- has **near minimum number of edges** (thus defines min-size connectivity constraints)
- edge weighted by likelihood of being broken given original task-related controller (thus edge with smaller weight indicates **less restriction towards original controller of connected robots**)

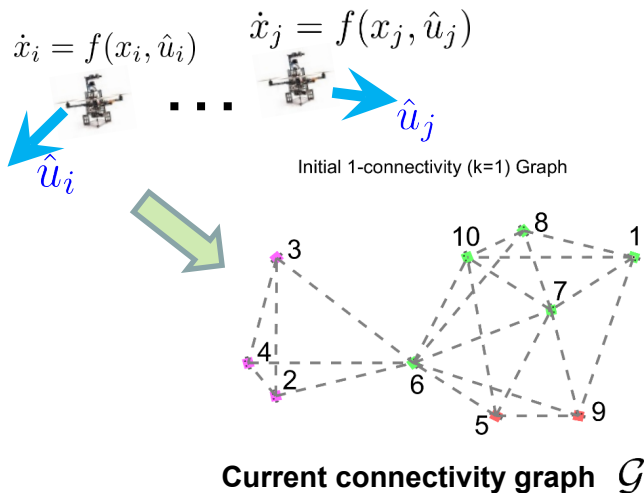


# ***k***-Connected Minimum Resilient Graph (***k***-CMRG)

**Step 1 (define connectivity constraints)** : A novel *k*-Connected Minimum Resilient Graph (*k*-CMRG) algorithm to find an *optimal k-connected graph*  $\mathcal{G}^{c*}$  to preserve/form that

- has **near minimum number of edges** (thus defines min-size connectivity constraints)
- edge weighted by likelihood of being broken given original task-related controller (thus edge with smaller weight indicates **less restriction towards original controller of connected robots**)

**Example: form a 2-connected graph**

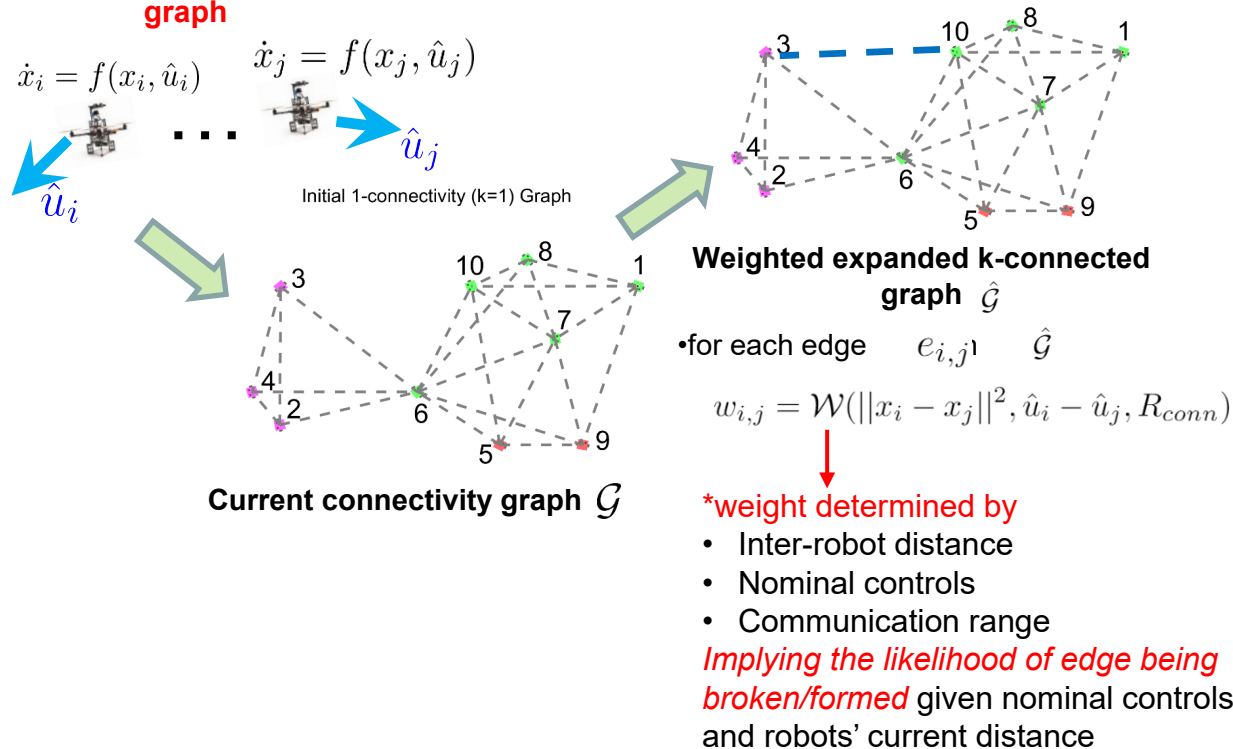


# ***k***-Connected Minimum Resilient Graph (***k***-CMRG)

**Step 1 (define connectivity constraints)** : A novel *k*-Connected Minimum Resilient Graph (*k*-CMRG) algorithm to find an *optimal k-connected graph*  $\mathcal{G}^{c*}$  to preserve/form that

- has **near minimum number of edges** (thus defines min-size connectivity constraints)
- edge weighted by likelihood of being broken given original task-related controller (thus edge with smaller weight indicates **less restriction towards original controller of connected robots**)

**Example: form a 2-connected graph**



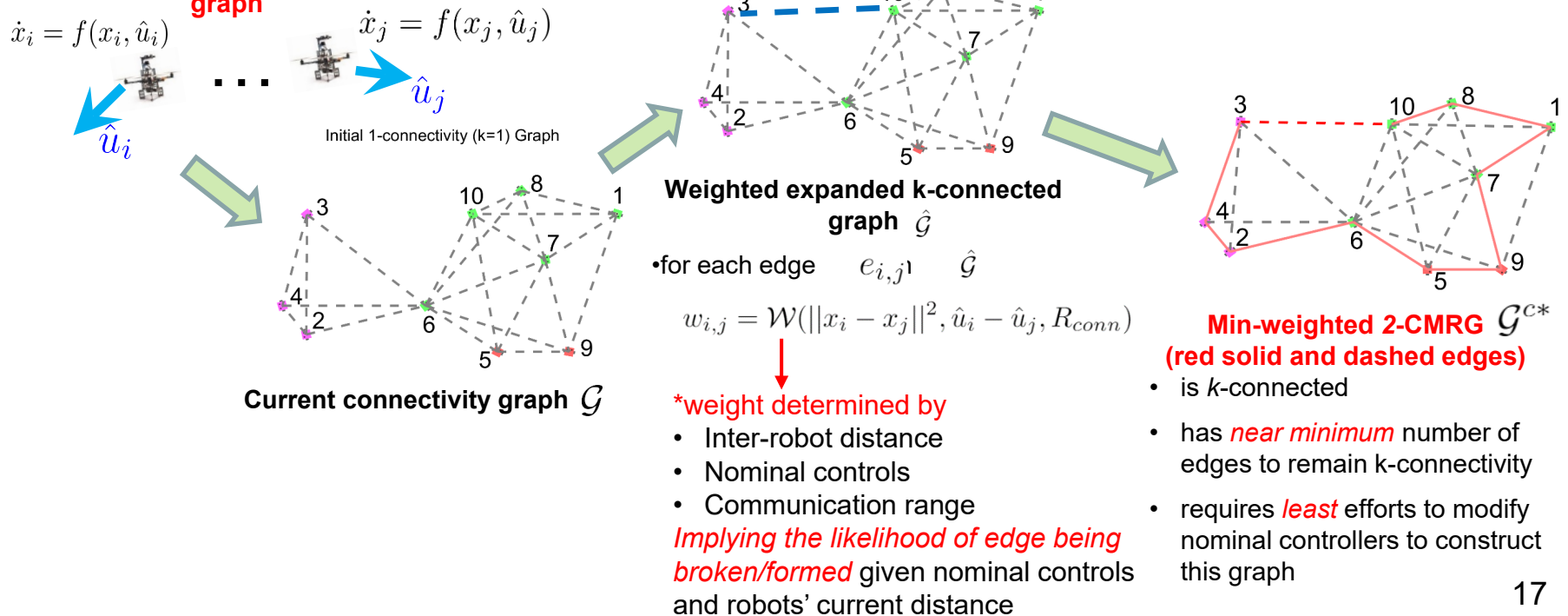


# ***k***-Connected Minimum Resilient Graph (***k***-CMRG)

**Step 1 (define connectivity constraints)** : A novel *k*-Connected Minimum Resilient Graph (*k*-CMRG) algorithm to find an *optimal k-connected graph*  $\mathcal{G}^{c*}$  to preserve/form that

- has **near minimum number of edges** (thus defines min-size connectivity constraints)
- edge weighted by likelihood of being broken given original task-related controller (thus edge with smaller weight indicates **less restriction towards original controller of connected robots**)

**Example: form a 2-connected graph**



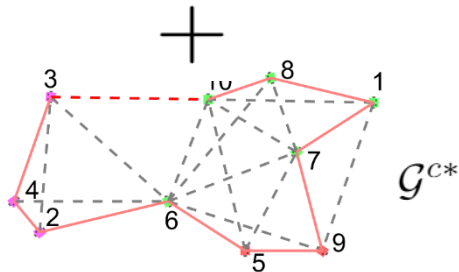
# Minimally Disruptive Connectivity Controller with k-CMRG

**Step 2 (derive constrained controller):** compute minimally modified controller from nominal  $\hat{u}_i$  subject to collision-free and defined connectivity constraints by  $\mathcal{G}^{c*}$  using finite-time control barrier functions (FCBF) [A. Li et al. IROS18]

$$\mathbf{u}^* = \arg \min_{\mathcal{G}^c, \mathbf{u}} \sum_{i=1}^n \|u_i - \hat{u}_i\|^2$$

s.t.  $\mathcal{G}^c = (\mathcal{V}, \mathcal{E}^c)$  is  $k$ -connected

$$\mathbf{u} \in \mathcal{B}^s(\mathbf{x}) \cap \mathcal{B}^c(\mathbf{x}, \mathcal{G}^c), \quad \|u_i\| \leq \alpha_i, \forall i = 1, \dots$$



$$\mathbf{u}^* = \arg \min_{\mathbf{u}} \sum_{i=1}^n \|u_i - \hat{u}_i\|^2$$

$$\text{s.t. } \mathbf{u} \in \mathcal{B}^s(\mathbf{x}) \cap \mathcal{B}^c(\mathbf{x}, \mathcal{G}^{c*}), \quad \|u_i\| \leq \alpha_i, \forall i = 1, \dots$$

**A standard QP with a set of linear control constraints using FCBF**

- Li, A., Wang, L., Pierpaoli, P. and Egerstedt, M., Formally correct composition of coordinated behaviors using control barrier certificates, IROS 2018

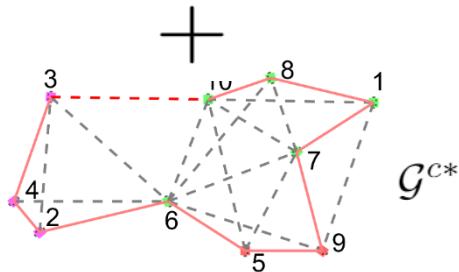
# Minimally Disruptive Connectivity Controller with k-CMRG

**Step 2 (derive constrained controller):** compute minimally modified controller from nominal  $\hat{u}_i$  subject to collision-free and defined connectivity constraints by  $\mathcal{G}^{c*}$  using finite-time control barrier functions (FCBF) [A. Li et al. IROS18]

$$\mathbf{u}^* = \arg \min_{\mathcal{G}^c, \mathbf{u}} \sum_{i=1}^n \|u_i - \hat{u}_i\|^2$$

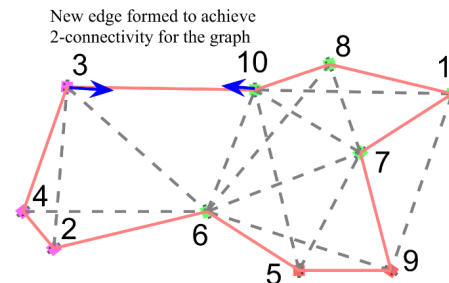
s.t.  $\mathcal{G}^c = (\mathcal{V}, \mathcal{E}^c)$  is  $k$ -connected

$$\mathbf{u} \in \mathcal{B}^s(\mathbf{x}) \cap \mathcal{B}^c(\mathbf{x}, \mathcal{G}^c), \quad \|u_i\| \leq \alpha_i, \forall i = 1, \dots$$



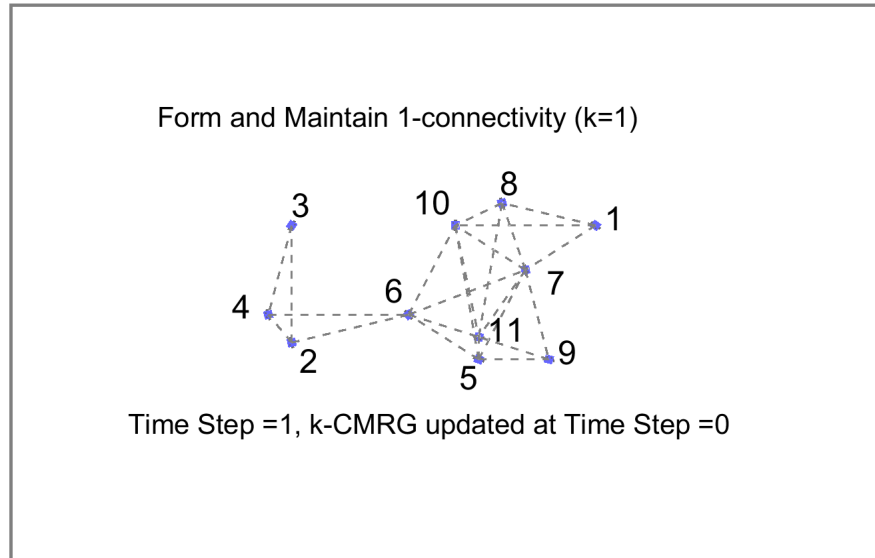
$$\mathbf{u}^* = \arg \min_{\mathbf{u}} \sum_{i=1}^n \|u_i - \hat{u}_i\|^2$$

s.t.  $\mathbf{u} \in \mathcal{B}^s(\mathbf{x}) \cap \mathcal{B}^c(\mathbf{x}, \mathcal{G}^{c*}), \quad \|u_i\| \leq \alpha_i, \forall i = 1, \dots$



# Results

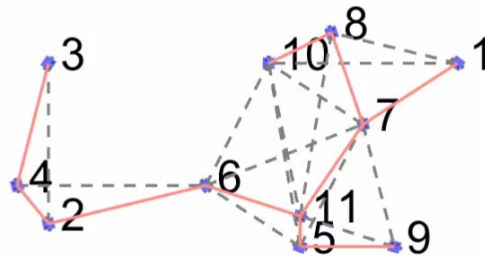
### Example 1: Connectivity enhancement from k=1 to k=4



11 robots with original controllers  $\hat{u}_i = 0$  under **increasing connectivity requirements**  
(initial multi-robot connectivity graph **is already 1-connected**)

# Example 1: Connectivity enhancement from $k=1$ to $k=4$

Form and Maintain 1-connectivity ( $k=1$ )

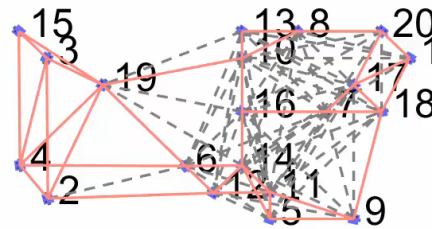


Time Step =1,  $k$ -CMRG updated at Time Step =0

1-connectivity already formed  
 Comes from legal formation  
 New  $k$ -CMRG satisfied  
 update  $k=2$   
 $k$ -CMRG preserved  
 Reconfiguring to form new  $k$ -CMRG  
 with robots/robots preserve  
 11 robots with original controllers  $\eta_i = 0$   
 (Our  $k$ -CMRG: robots reconfigure to maintain required connectivity over time)  
 ( $k=1$ )

**Example 2: Maintain 3-connectivity ( $k=3$ ) with robot failures**  
**Self-healing via reconfiguration**

Form and Maintain 3-connectivity ( $k=3$ )

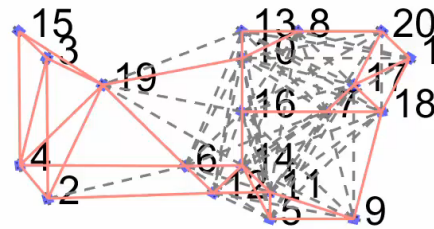


Time Step =1,  $k$ -CMRG updated at Time Step =0

Our  $k$ -CMRG  
Robots **reconfigure** to **recover** connectivity

**Example 2: Maintain 3-connectivity ( $k=3$ ) with robot failures**  
**Self-healing via reconfiguration**

Form and Maintain 3-connectivity ( $k=3$ )

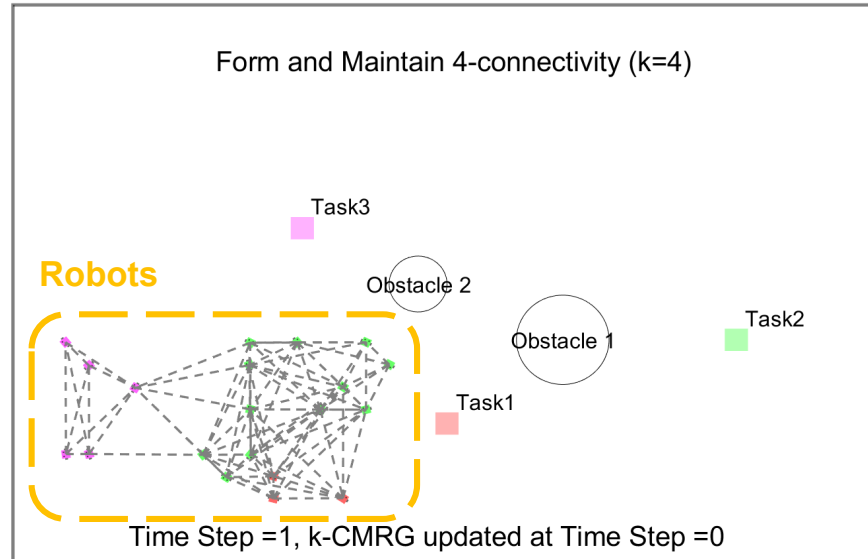


Time Step =1,  $k$ -CMRG updated at Time Step =0

Our  $k$ -CMRG  
Robots **reconfigure** to **recover** connectivity



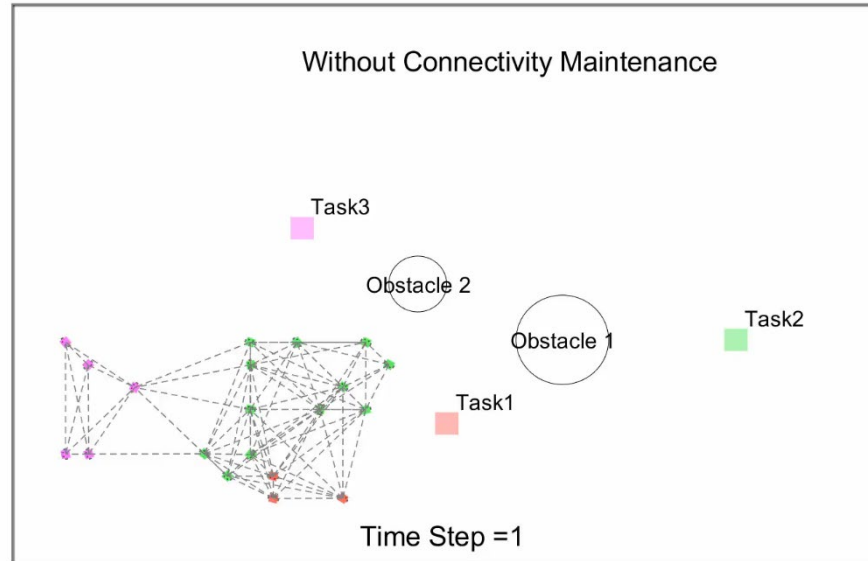
### Example 3: Resilient Connectivity Maintenance with Dynamic Task



20 robots tasked with 3 behaviors by the pre-assigned subgroups

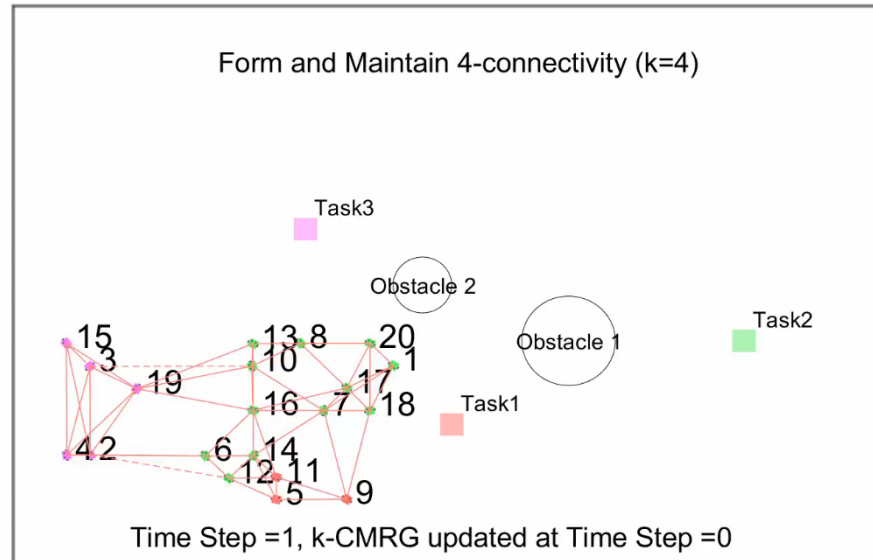
**Goal:** executing tasks while achieving *required dynamic connectivity*  
with *obstacles* and *robot failures*

### Example 3: Resilient Connectivity Maintenance with Dynamic Task



**Original task-related behaviors without connectivity consideration**  
**(robots get disconnected quickly)**

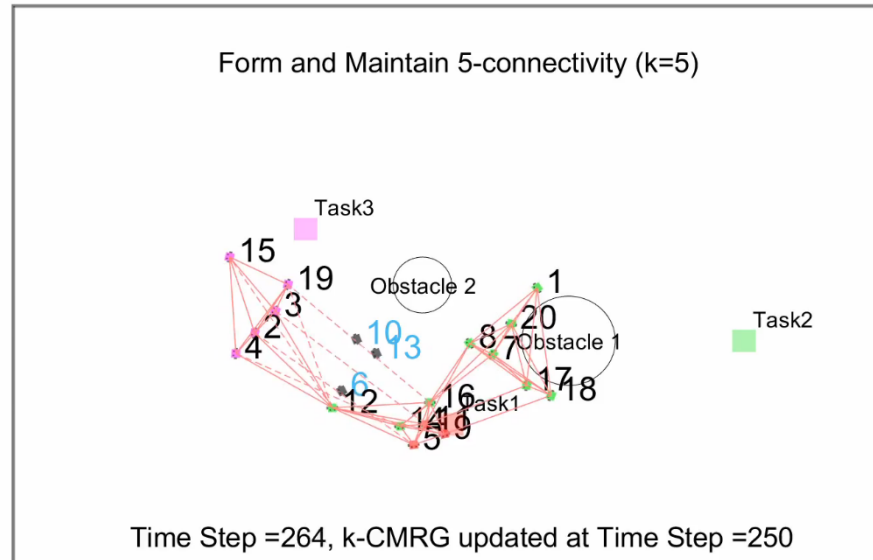
### Example 3: Resilient Connectivity Maintenance with Dynamic Task



Minimally disruptive task execution with **our k-CMRG** to achieve **required dynamic connectivity**

**At time step 250: Robot 6, 10, 13 fail and required k increases to 5**

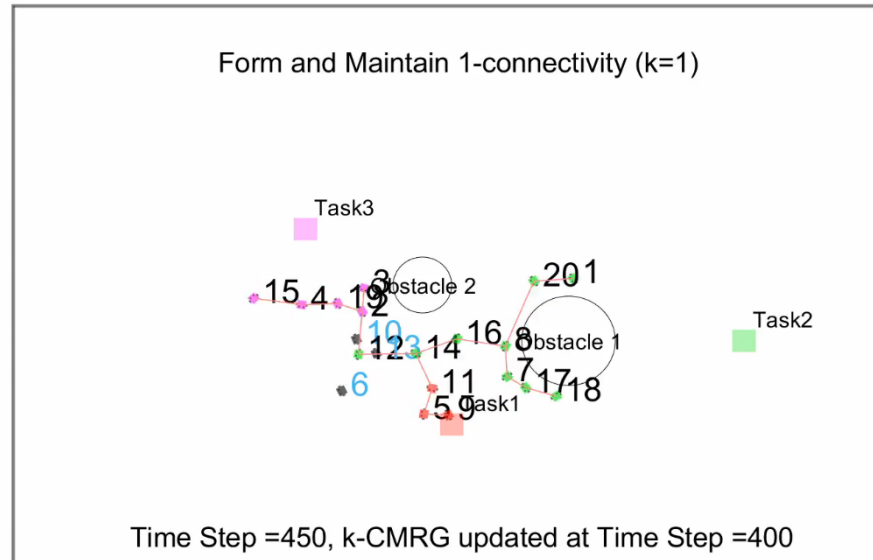
### Example 3: Resilient Connectivity Maintenance with Dynamic Task



Minimally disruptive task execution with **our k-CMRG** to achieve **required dynamic connectivity**

**From time step 250-450:** Robots reconfigure to achieve required  **$k=5$**

### Example 3: Resilient Connectivity Maintenance with Dynamic Task



Minimally disruptive task execution with **our k-CMRG** to achieve **required dynamic connectivity**

**From time step 451-1200:** Robots move to tasks and ensure updated connectivity  **$k=1$**

# Conclusions & Future Work

- A novel *bi-level* optimization framework to *maintain* and *enhance* multi-robot connectivity with *provable minimal disruption* to primary tasks
- Ensures *any demanded  $k$ -connectivity* of multi-robot graph *regardless of initial connectivity*
- **Resilient** to reduction in connectivity of multi-robot communication graph due to robot arrival and removal

**Future Work:** Field test and decentralized computation to improve efficiency

## List of Publications, Awards, Honors, etc.

### Attributed to the Grant

- Ding, Yifan, Luo, Wenhao, Sycara, Katia Heuristic-Based Multiple Mobile Depots Route Planning for Recharging Persistent Surveillance Robots, IROS, Macau, China, November 14-18, 2019..
- Luo, Wenhao, Sycara, Katia Minimum k-connectivity Maintenance for Robust Multi-Robot Systems, IROS, Macau, China, November 4-8, 2019
- Luo, Wenhao, Sycara, Katia Voronoi-based Coverage Control with Connectivity Maintenance for Robotic Sensor Networks, Multi-Robot and Multi-Agent Systems (MRS), Rutgers, August 22-23, 2019.
- Ding, Yifan, Luo, Wenhao, Sycara, Katia Multi-Mobile Depots in Multi-Robot Route Planning. In Multi-Robot and Multi-Agent Systems (MRS), Rutgers, August 22-23, 2019.
- Luo. W., Nam, C., Kantor, G., Sycara, K., Distributed Environmental Modeling and Adaptive Sampling for Multi-Robot Sensor Coverage, AAMAS, May 12-17, Montreal, 2019.
- Lukas, Chrupa, Jakub Gemrot, and Martin Pilat, Planning and acting with non-deterministic events: Navigating between safe states, In proceedings of the Thirty Fourth AAAI conference on Artificial Intelligence (AAAI-20).
- Luo, W., Chakraborty, N., and Sycara, K., Minimally Disruptive Connectivity Enhancement for Resilient Multi-Robot Teams, accepted to *IROS* 2020