COLORADO SCHOOL OF MINES
engineering the way

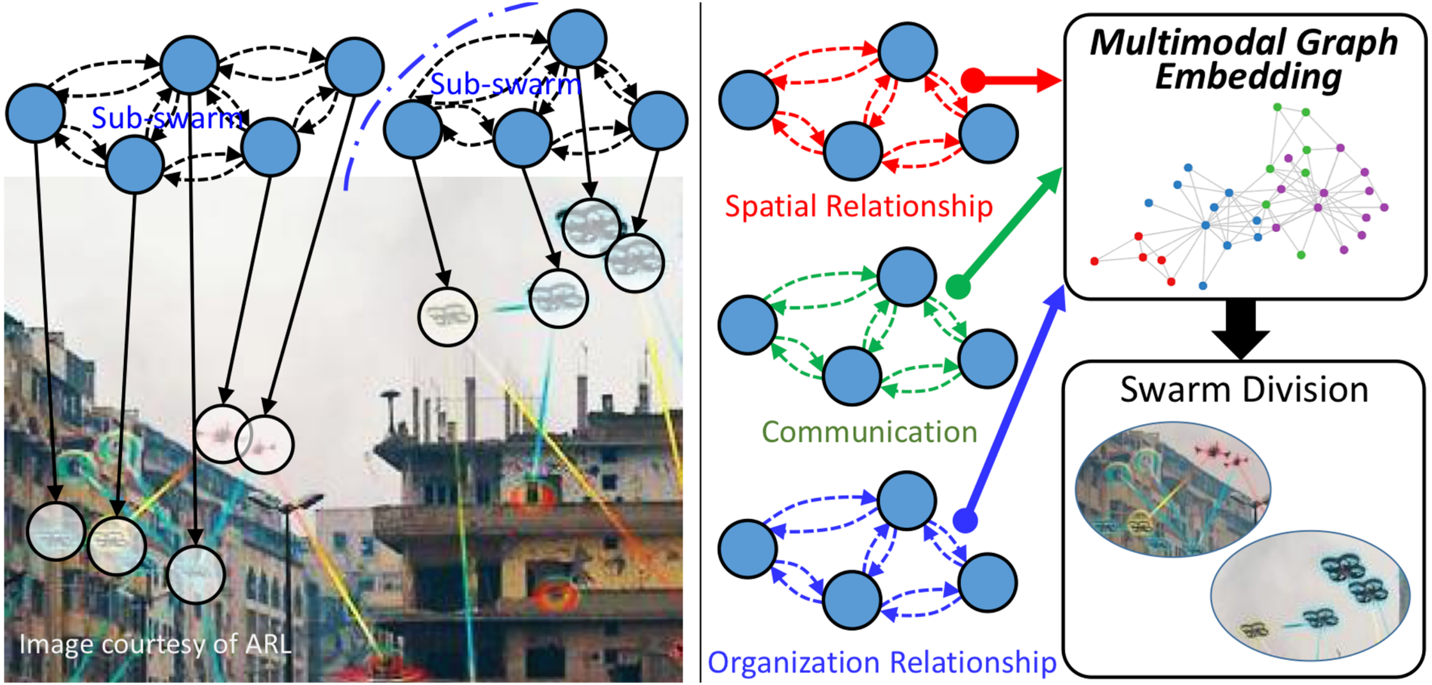
Representing Multi-Robot Structure through Multimodal Graph Embedding for the Selection of Robot Teams

2020 International Conference on Robotics and Automation

Brian Reily[1], Christopher Reardon[2], and Hao Zhang[1]

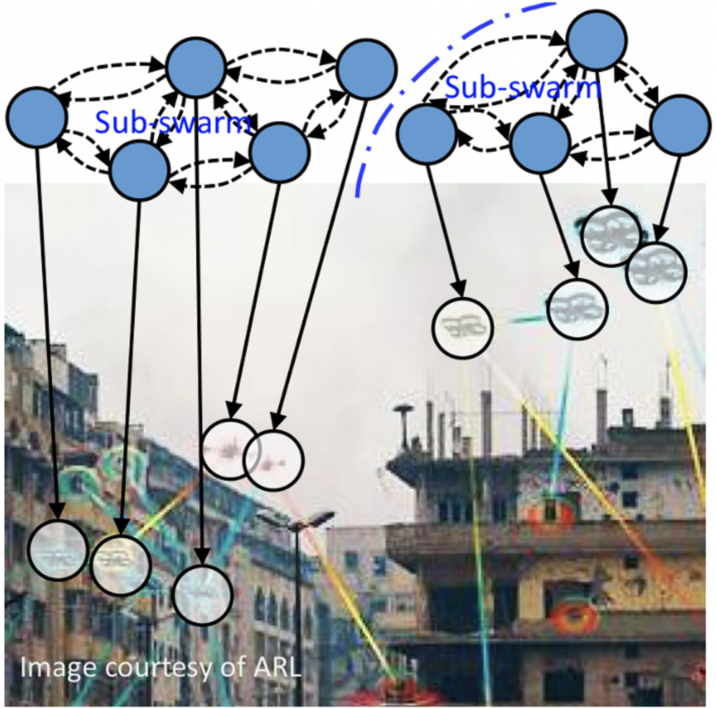
1: Human-Centered Robotics Lab, Colorado School of Mines (http://hcr.mines.edu)
2: U.S. Army Research Laboratory

Overview


Sub-swarm
Sub-swarm
Image courtesy of ARL
Spatial Relationship
Communication
Organization Relationship
Multimodal Graph Embedding
Swarm Division

Motivation

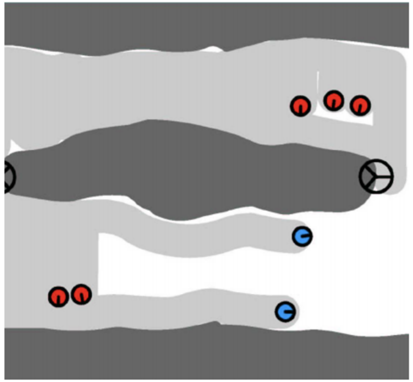
- Identifying *effective teams* allows a multi-robot system to accomplish multiple separate tasks simultaneously or over a large area.
- Large multi-robot systems are cognitively difficult for humans to understand and command – breaking into smaller teams eases this burden.



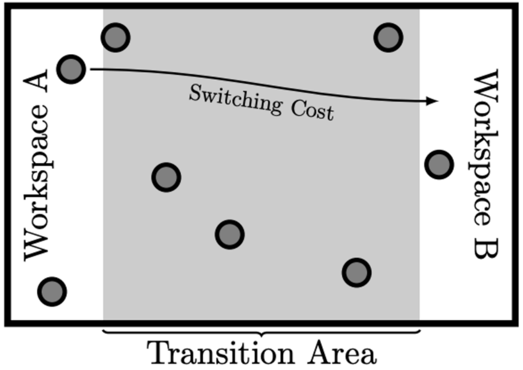
Existing Work

Previous approaches either:

→ Assigned regions purely based on spatial relationships



[1]



[2]

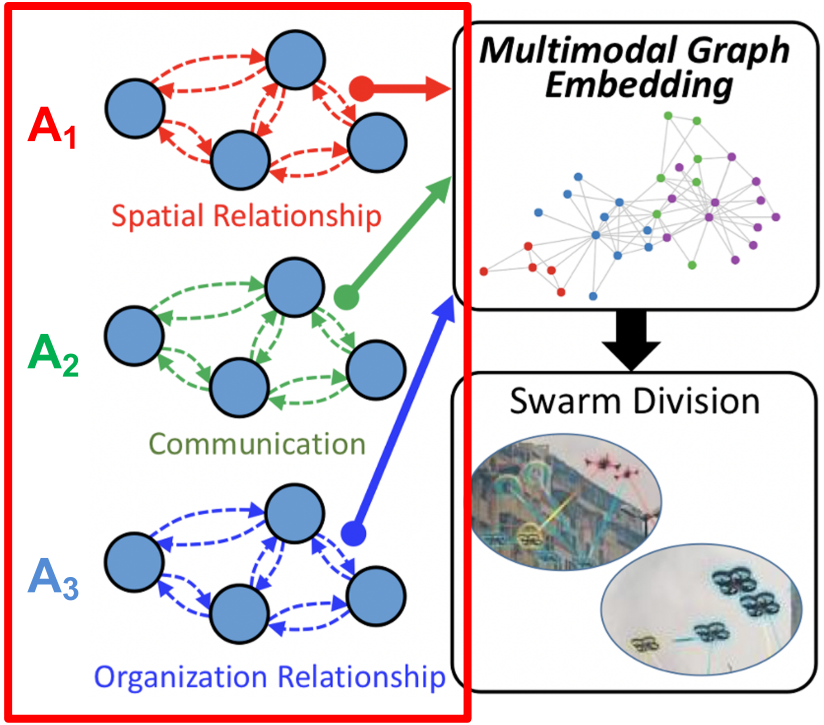
← Allocated tasks to individuals or teams based on explicit knowledge of the tasks

[1]: I. Rekleitis, V. Lee-Shue, A. P. New, and H. Choset, “Limited communication, multi-robot team based coverage,” in IEEE International Conference on Robotics and Automation, 2004.
[2]: M. Castillo-Cagigal, A. Brutschy, A. Gutie ́rrez, and M. Birattari, “Temporal task allocation in periodic environments,” in International Conference on Swarm Intelligence, 2014.

Our Contribution

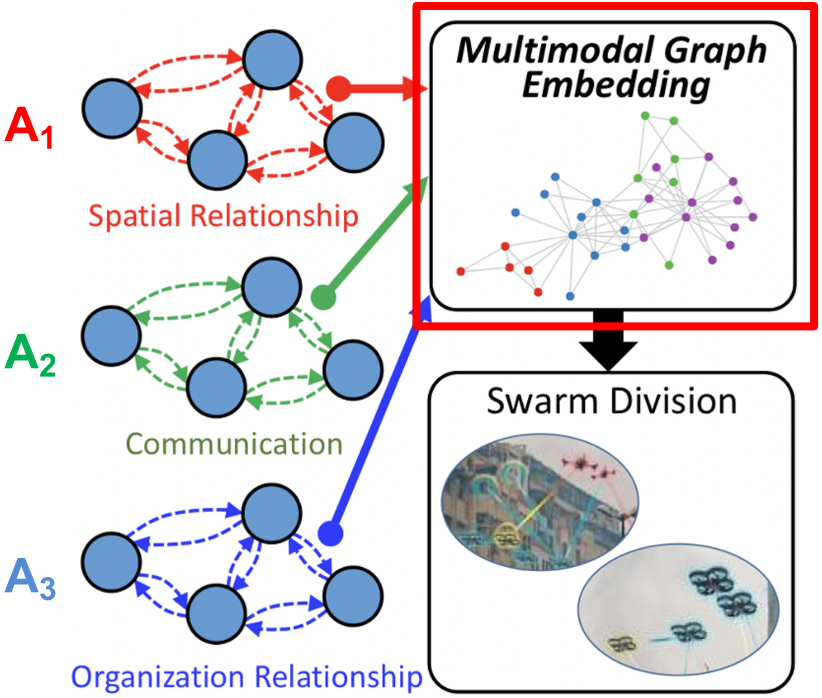
- We formulate robot team selection as a graph-based embedding and clustering problem, modeling multiple relationships of robots and fusing them into a unified representation.
- We evaluate our approach on expert-defined team formations, large-scale simulated multi-robot systems, and teams of physical robots, showing that it is effective in identifying robotic teams and obtains superior performance over existing graph-based division methods.

Problem Formulation



We propose a novel multimodal graph embedding approach that models multiple relationships of robots using graphs and fuses them into a unified representation to identify robotic teams.

Problem Formulation



These multiple adjacency matrices $\mathbf{A}_{\mathbf{m}}$ each describe a relationship and our approach fuses them into a unified representation:

$$\mathbf{S} = \sum_{l=1}^{L} \alpha^{l} \sum_{m=1}^{M} w_m \mathbf{A}_m^{l}$$

This representation is based on the Katz index, a social network scoring algorithm where longer paths between vertices result in lower scores in $\boldsymbol{S}$.

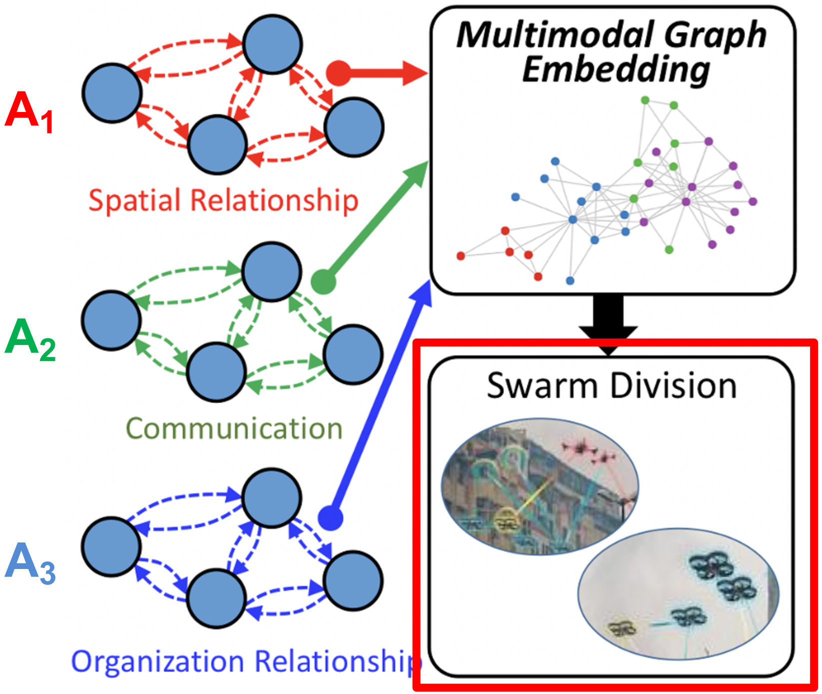
Problem Formulation

$$\mathbf{S} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^T$$

We create a fixed-length and lower dimensional representation from S by performing SVD and fusing the first K left and right eigenvectors into a final representation $\mathbf{X}$.

$$\mathbf{X} = \begin{array}{c} \left[\begin{array}{ccc} u_{1,1} & \cdots & u_{1,K} \\ \vdots & \ddots & \vdots \\ u_{n,1} & \cdots & u_{n,K} \\ \vdots & \ddots & \vdots \\ u_{N,1} & \cdots & u_{N,K} \end{array}\right] \left[\begin{array}{ccc} v_{1,1} & \cdots & v_{1,K} \\ \vdots & \ddots & \vdots \\ v_{n,1} & \cdots & v_{n,K} \\ \vdots & \ddots & \vdots \\ v_{N,1} & \cdots & v_{N,K} \end{array}\right] \end{array} \begin{array}{l} \text{Agent 1} \\ \vdots \\ \text{Agent } n \\ \vdots \\ \text{Agent } N \end{array}$$

Problem Formulation



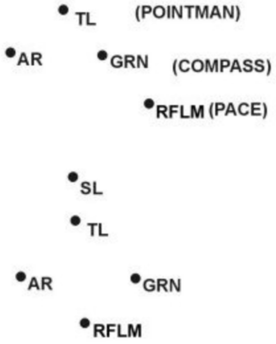
Clustering methods can then be used to identify teams from $\mathbf{X}$, with the number of clusters corresponding to the number of teams necessary.

Evaluation on Expert-Defined Teams

Expert-defined teams were identified from the US Army field manual on infantry tactics.

These provide known:

- Spatial relationships
- Hierarchy
- Communication relationships
- … and team assignments



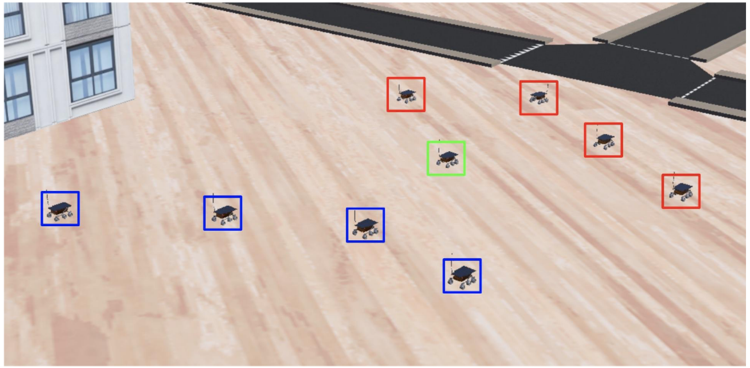
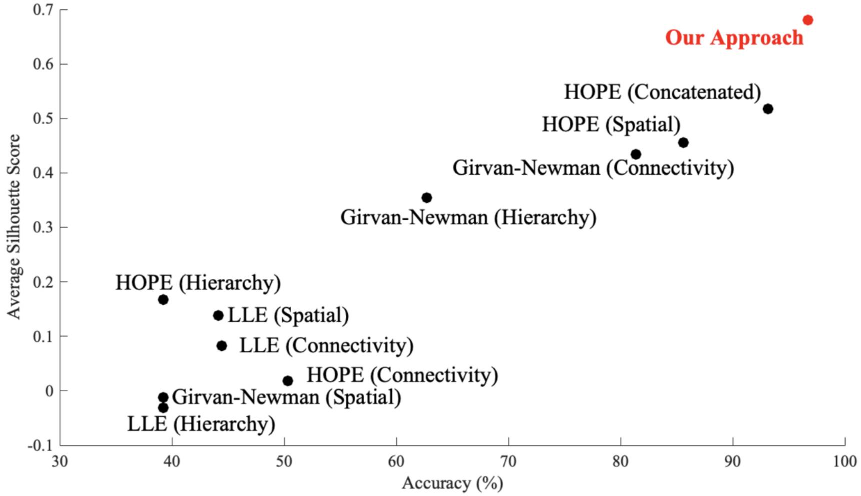


Figure from: Department of the Army. U.S. Army Field Manual 3-21.9, 2017

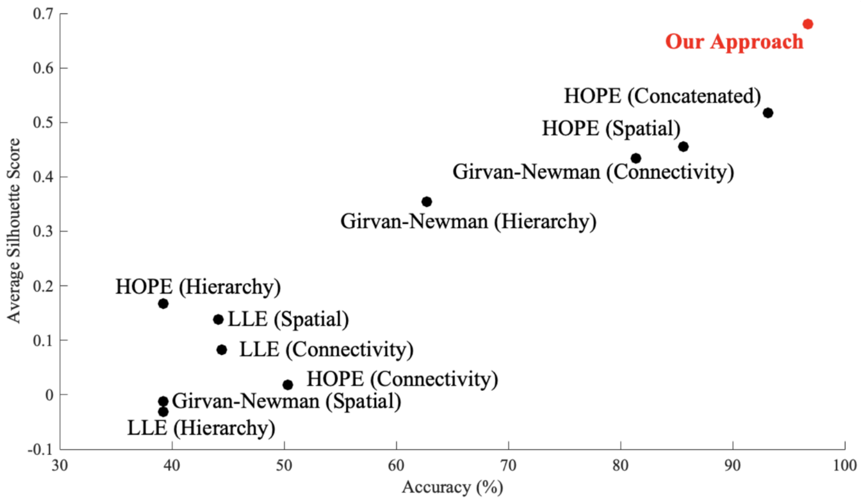
Evaluation on Expert-Defined Teams



- We compare to other graph clustering and embedding approaches.
- We also consider a clustering metric called the silhouette score in order to quantify how well our approach works on simulated swarms without ground truth labels.

[HOPE]: M. Ou, P. Cui, J. Pei, Z. Zhang, and W. Zhu, “Asymmetric transitivity preserving graph embedding,” in ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, 2016.
[LLE]: S. T. Roweis and L. K. Saul, “Nonlinear dimensionality reduction by locally linear embedding,” Science, vol. 290, no. 5500, pp. 2323–2326, 2000.
[Girvan-Newman]: M. E. J. Newman and M. Girvan, “Finding and evaluating community structure in networks,” Physical Review E, vol. 69, p. 026113, 2004.

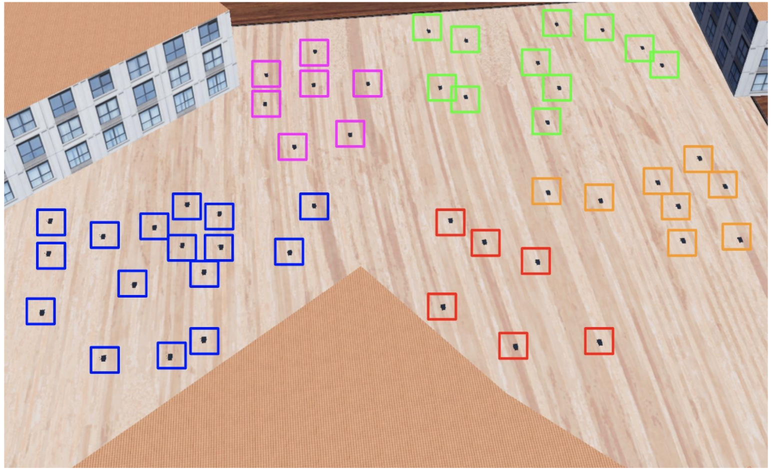
Evaluation on Expert-Defined Teams



A linear relationship exists between accuracy on these expert-defined teams and the resulting silhouette score, validating this as a metric for multi-robot systems without ground truth data.

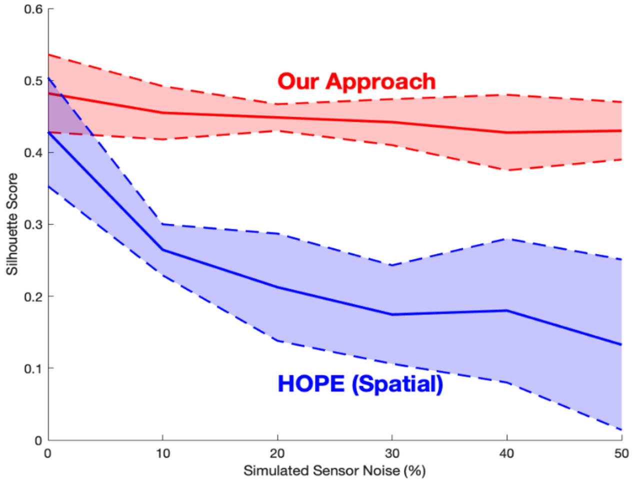
Evaluation on Simulated Swarms

- We simulate large scale swarms up to 50 robots, using the silhouette score as a metric.
- Our approach consistently produces the highest scores, showing it identifies the most effective teams.

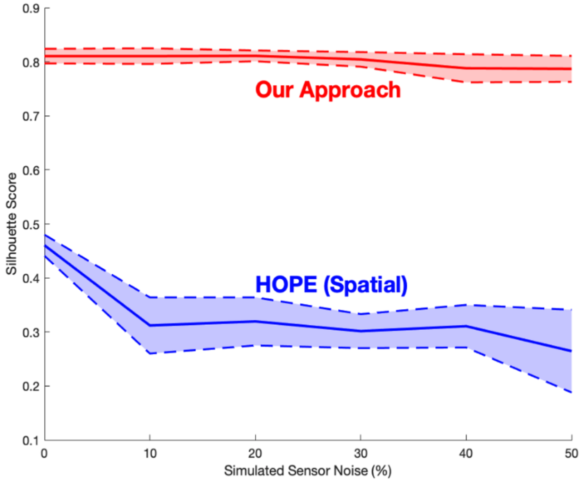


Robustness to Noise

We also evaluated the robustness of our approach by adding noise to the positions of agents in the expert-defined teams.



Small Team



Large Team

Thanks!

- We formulate robot team selection as a graph-based embedding and clustering problem, modeling multiple relationships of robots and fusing them into a unified representation.
- We show that our approach is effective in identifying robotic teams and obtains superior performance over existing graph-based division methods.

Thanks!

- We formulate robot team selection as a graph-based embedding and clustering problem, modeling multiple relationships of robots and fusing them into a unified representation.
- We show that our approach is effective in identifying robotic teams and obtains superior performance over existing graph-based division methods.

Questions?

Contact Us: hzhang@mines.edu / breily@mines.edu
http://hcr.mines.edu

This work was partially supported by ARL DCIST CRA W911NF-17- 2-0181, ARO W911NF-17-1-0447, and NSF CNS-1823245.