Learning Altruistic Collaboration in Heterogeneous Multi-Team Systems

Riwa Karam, Ruoyu Lin, Brooks A. Butler, and Magnus Egerstedt
Electrical Engineering and Computer Science

UCI Samueli School of Engineering
University of California, Irvine

Robot Ecology Lab
UCI Samueli School of Engineering

Website

LinkedIn

Abstract

Multi-Team System
- Multiple teams of robots in distinct regions of interests

Heterogeneity
- Robots across the system possess heterogeneous capabilities, i.e., mission contributions

Collaboration [1]
- Cooperative and coordinated work towards a shared goal through complementary capabilities

Altruism
- Altruistic decision-making inspired by Hamilton's Rule from ecology

Introduction

- A fundamental challenge in multi-robot systems is **resource and task allocation**, where different resources and/or tasks must be assigned to different agents to optimize overall system performance.
- Typical multi-robot allocation formulations assume independent or additive contributions of agents, where the performance of a team depends primarily on the **number** of assigned robots [2].
- In **heterogeneous** systems, robots may possess complementary sensing, actuation, or computational capabilities, and the contribution of a robot depends on the composition of the team it joins.
- Graph neural networks (GNNs) provide a framework for learning decentralized policies over relational structures, enabling scalable decision-making in multi-robot systems.
- Hamilton's rule characterizes altruistic behavior through a trade-off between cost and benefit weighted by genetic relatedness [3].

Select References

[1]: **Karam, R.**, Nguyen, A. A., Lin, R., Martin, D. R., Morales, D., Butler, B. A., & Egerstedt, M. (2026). "*Collaboration in Multi-Robot Systems: Taxonomy and Survey over Frameworks for Collaboration*". arXiv preprint arXiv:2603.23898, (submitted to Control Systems Magazine).

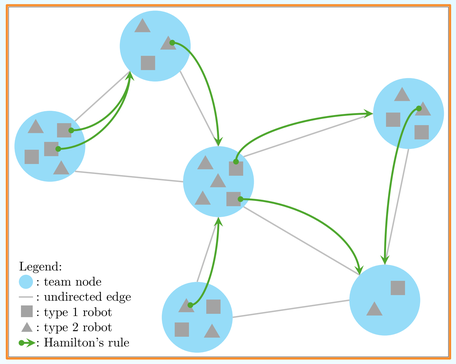
[2]: **Karam, R.**, Lin, R., Butler, B. A., & Egerstedt, M. (2025, December). "*Resource allocation with multi-team collaboration based on Hamilton's rule*". In Proceedings of the IEEE Conference on Decision and Control (CDC) (pp. 6891-6898). IEEE.

[3]: Hamilton, W. D. (1964). "*The genetical evolution of social behaviour. II*". Journal of theoretical biology, 7(1), 17-52.

Acknowledgements

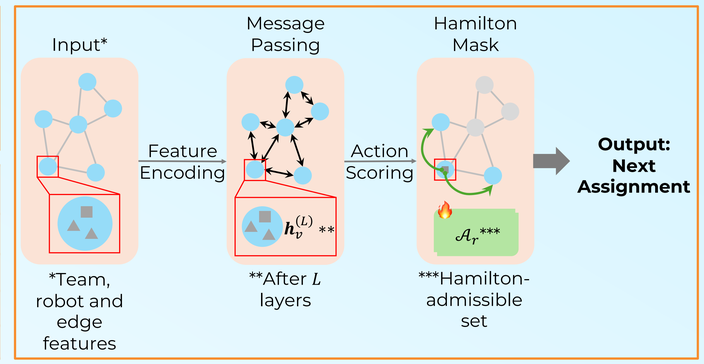
The authors want to thank Professor Yanning Shen and Dr. Alex Nguyen for helpful discussions.

Methodology



$$
\begin{aligned}
\max \quad & \text{global performance - global cost} \\
\text{s.t.} \quad & \text{assignment constraints} \\
& \text{mission constraints} \\
& \dots
\end{aligned}
$$

Hamilton's Rule [3]	Hamilton's Rule for Team-Level Heterogeneous Resource Allocation
$rB \geq C$	$r_{ij}\, B_{r,j}(\mathcal{S}_j) > C_{r,i}(\mathcal{S}_i)$
r	$r_{ij} = \frac{w_j}{w_i} \quad and \quad r_{ji} = \frac{w_i}{w_j} = \frac{1}{r_{ji}}$
B	$B_{r,j}(\mathcal{S}_j) = \mathcal{F}_j(\mathcal{S}_j \cup \{r\}) - \mathcal{F}_j(\mathcal{S}_j)$
C	$C_{r,i}(\mathcal{S}_i) = \mathcal{F}_i(\mathcal{S}_i) - \mathcal{F}_i(\mathcal{S}_i \setminus \{r\})$

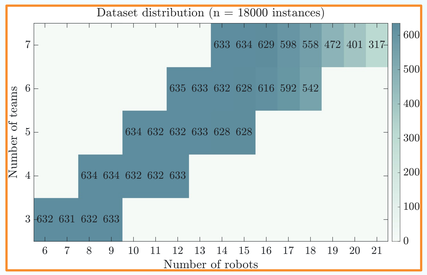


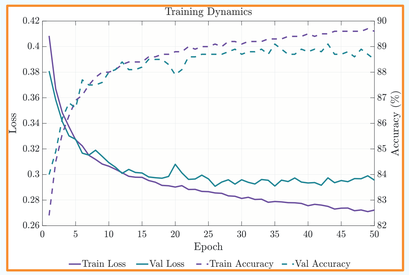
Tractability and **scalability** problem:
Solving an NP-hard problem at each iteration of the algorithm!

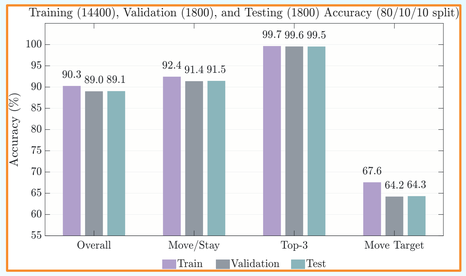
Learning-Based Solution

GNN policy to approximate the solution of the problem at each iteration

Results

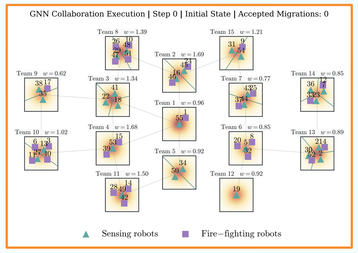


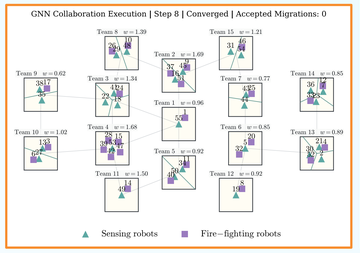




RUNTIME SCALING OF THE EXACT OPTIMIZATION AND THE GNN POLICY. EXACT AND GNN TOTAL RUNTIMES ARE FULL ITERATIVE EXECUTION RUNTIMES. MEAN STEP RUNTIMES ARE COMPUTED FROM THE PER-STEP RUNTIME EXECUTION.

Teams	Robots	Opt. Total (s)	Opt. Mean Step (s)	Opt. Steps	GNN Total (s)	GNN Mean Step (s)	GNN Steps
3	9	0.051	0.025	2	0.048	0.012	4
4	12	0.090	0.030	3	0.012	0.006	2
5	15	0.781	0.390	2	0.009	0.005	2
6	18	35.4	11.8	3	0.170	0.034	5
7	21	∞	–	1	0.201	0.050	4
8	24	∞	–	–	0.298	0.075	4
9	27	∞	–	–	0.816	0.204	4
10	30	∞	–	–	0.658	0.219	3
15	45	∞	–	–	1.957	0.326	6
25	75	∞	–	–	2.787	0.697	4
35	105	∞	–	–	16.3	2.335	7
40	120	∞	–	–	36.0	2.001	18
45	135	∞	–	–	48.5	2.425	20
50	150	∞	–	–	55.3	2.767	20





This work provides the following advantages:

- Decentralization
- Heterogeneous Collaboration
- Tractable and Scalable Resource Allocation
- Near-optimal approximation of the NP-hard optimization
- Ecology-inspired altruistic and local decision-making
- Convergence

Check out cool videos of the GNN in action both in simulation and on real robotic experiments!