SSM
Scuola Superiore Meridionale

MERC PhD Project Proposal 2024/2025

Title of the research project:

Harnessing Complex Systems for Control: a learning-based control approach to multi-robot shepherding problems in search & rescue operations (PNRR-PA)

Keywords (up to five)

Multiagent Systems Control, Deep Reinforcement Learning, Dimensionality Reduction

Supervisors (at least two from two different areas):

Supervisor 1 (name, contact details, homepage, area of expertise)
Mario di Bernardo (membro del collegio MERC)

Supervisor 2 (name, contact details, homepage, area of expertise)
Francesco De Lellis (RTD-A, Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione) – Reinforcement Learning, learning-based control, machine learning)

Supervisor 3 (name, contact details, homepage, area of expertise)
Mirco Musolesi, University College London, MERC Board member

Project description (max 5000 characters)

Search and rescue missions in complex, unstructured environments—such as post-disaster urban areas or hazardous landscapes—present major challenges for autonomous systems. Coordinating heterogeneous agents, including drones and ground robots, is critical to locating, guiding, and evacuating individuals safely. This requires control strategies that are robust, adaptive, and capable of operating under uncertainty and limited information.

A compelling abstraction for these scenarios is the shepherding control task, where active agents (herders) guide passive agents (targets) to a goal region through indirect interactions. Practically, this models UAVs or mobile robots collaboratively guiding civilians or robotic units through hazardous environments while avoiding obstacles and unsafe zones.

Conventional model-based approaches, while effective in simple settings, rely on fixed models and handcrafted rules, limiting their adaptability and scalability in real-world situations. This project addresses these limitations by proposing a data-driven, multi-agent control framework based on Reinforcement Learning (RL), with a focus on Multi-Agent Reinforcement Learning (MARL). The goal is to develop adaptive, scalable, and interpretable policies capable of emergent coordination in demanding rescue scenarios.

Shepherding is a particularly suitable benchmark due to its complexity and real-world relevance. The environment is often unstructured, with limited observability and dynamic hazards. Agents are heterogeneous, combining UAVs and ground rovers with different sensing and actuation capabilities. Moreover, the absence of a reliable system model makes the problem ideal for model-free solutions.

The project will investigate a range of target behaviors, from passive agents exhibiting random motion to more sophisticated dynamics like evasion and flocking. These variations enable a thorough assessment of the generalization and robustness of the control policies. Herders will also operate under realistic constraints, such as partial observability and limited communication. Their physical heterogeneity motivates the use of mixed cooperative-competitive MARL frameworks, where agents must both collaborate and specialize—making this a canonical setting for decentralized decision-making.

To build effective policies, the project will explore the use and extensions of state-of-the-art algorithms and tools such as Proximal Policy Optimization (PPO) and its multi-agent extension (MAPPO), Convolutional Neural Networks, Graph Neural Networks and Reinforcement Learning. Policies will be represented by neural networks trained through interaction with the environment. To address task complexity, the project will explore various control architectures, including hierarchical reinforcement learning, which decomposes high-level goals into subtasks like target selection and group coordination. Hierarchical approaches promote modularity, improve sample efficiency, and facilitate transferability across environments. Additionally, to address scalability, dimensionality reduction techniques such as autoencoders will be explored to compress system dynamics into lower-dimensional representations, enabling more efficient learning.

Despite recent advances, MARL still lacks formal guarantees, particularly in safety-critical applications. Policy convergence, stability, and robustness remain difficult to analyze. To address these gaps, the project will develop new RL frameworks that embed control-theoretic principles into the learning process. In particular, it will explore reward shaping strategies that connect classical control concepts with modern RL techniques, aiming to produce policies that are both empirically effective and theoretically grounded.

The proposed methods will be validated through high-fidelity simulations of shepherding tasks in increasingly realistic environments and experiments in a mixed reality setting to be developed at the Scuola Superiore Meridionale. A dedicated case study will focus on search and rescue operations in the Campi Flegrei volcanic region. In collaboration with local partners, including the Osservatorio Vesuviano and the CNR-STEM Institute, the project will build data-informed simulations to assess the feasibility and societal relevance of the developed methods.

Ultimately, this research aims to bridge the gap between reinforcement learning and control theory, advancing both the theoretical foundations and practical deployment of adaptive, multi-agent systems in high-stakes real-world scenarios.

Relevance to the MERC PhD Program (max 2000 characters)

Briefly describe how this project fits within the scope of the MERC PhD program describing its interdisciplinary aspects, relevance in application and beneficiaries.

This research project directly addresses MERC's core mission of developing new methodological approaches for modeling and controlling complex, interdependent systems under uncertainty. The proposed shepherding control framework exemplifies the program's focus on creating interdisciplinary solutions with significant societal impact, specifically targeting disaster response scenarios. The project embodies MERC's systems-oriented approach by integrating control theory, multi-agent reinforcement learning, and risk analysis to manage emergent behaviors in complex environments. This aligns perfectly with the program's emphasis on understanding cascade effects and developing resilient engineering solutions for both natural and anthropogenic hazards. Methodologically, the research combines mathematical modelling, stochastic processes, and data-driven techniques—precisely the interdisciplinary toolkit that MERC aims to cultivate in its researchers. The shepherding control problem serves as an ideal testbed for MERC's virtuous cycle between theory and application. The project intersects multiple MERC application areas, including automation and control engineering, mathematical engineering, and natural hazard analysis. The mixed reality experimental environment will enable rigorous testing of theoretical guarantees under realistic uncertainty conditions.

Key references

1. A. Lama and M. di Bernardo, “Shepherding and herdability in complex multiagent systems,” Phys. Rev. Res., vol. 6, p. L032012, 2024.
2. J. K. Gupta, M. Egorov, and M. Kochenderfer, “Cooperative multiagent control using deep reinforcement learning,” in Autonomous Agents and Multiagent Systems, pp. 66–83, 2017.
3. F. De Lellis, M. Coraggio, G. Russo, M. Musolesi and M. di Bernardo, "Guaranteeing Control Requirements via Reward Shaping in Reinforcement Learning," in *IEEE Transactions on Control Systems Technology*, vol. 32, no. 6, pp. 2102-2113, 2024.
4. C. Yu, A. Velu, E. Vinitsky, J. Gao, Y. Wang, A. Bayen, and Y. Wu, “The surprising effectiveness of ppo in cooperative multi-agent games,” Advances in neural information processing systems, vol. 35, pp. 24611–24624, 2022.
5. M. Han, L. Zhang, J. Wang and W. Pan, "Actor-Critic Reinforcement Learning for Control With Stability Guarantee," in *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6217-6224, 2020
6. Wang, Yasi, Hongxun Yao, and Sicheng Zhao. "Auto-encoder based dimensionality reduction." *Neurocomputing* vol. 184, pp. 232-242, 2016.
7. John Schulman, Sergey Levine, Pieter Abbeel, Michael Jordan, Philipp Moritz, “Trust Region Policy Optimization”, Proceedings of the International Conference on Machine Learning, PMLR 37:1889-1897, 2015.
8. Schulman, John, et al. "High-dimensional continuous control using generalized advantage estimation." arXiv:1506.02438, 2015.
9. D. Strombom, R. Mann, A. Wilson, S. Hailes, A. Morton, D. Sumpter, and A. King, “Solving the shepherding problem: Heuristics for herding autonomous, interacting agents,” Journal of The Royal Society Interface, vol. 11, 2014.

Joint supervision arrangements

Describe joint supervision arrangements, e.g. weekly/monthly meetings with one or both supervisors, how will the joint supervision be split etc

Supervision will occur through regular weekly meetings with at least one of the supervisors and regular meetings with all the supervising team which will be extended when the student is abroad with his hosting supervisor at the foreign institution.

Location and length of the study period abroad (min 12 months)

Give details of the foreign research institution where the student will be host together with the full name and contacts of the foreign host. Please indicate if the foreign institution has already agreed to host the student and when the student is expected to travel abroad.

As this is a PNRR-PA Scholarship the student will spend 6 months at the CNR-STEM institute and the Osservatorio Vesuviano and minimum 6 months abroad. A possible hosting institution can be University College London, where he will be supervised by Prof Mirco Musolesi (MERC Board member). For the robotic implementation, a period of stay is envisaged at the Univerisity of Konstanz, Centre of Excellence in Animal Behaviour, under the supervision of Dr Andrea Giovanni Reina.

Any other useful information

E.g. involvement of stakeholders, industrial partners, other research institutions etc, funded research projects related to the proposed activity etc - CNR STEM Institute - Protezione Civile/Osservatorio Vesuviano Related Research Project: PRIN 2022 MENTOR

Please return this form via email by no later than 16th April 2025