MERC PhD Project Proposal 2024/2025

Title of the research project:

Macroscopic control of large-scale leader-follower multi-agent systems: closing the gap between theory and applications

Keywords (up to five)

Large-scale multi-agent systems, Shepherding, Control of PDEs, Leader-Follower control

Supervisors (at least two from two different areas):

Supervisor 1 (name, contact details, homepage, area of expertise)
Mario di Bernardo, University of Naples Federico II (MERC Board Member)

Supervisor 2 (name, contact details, homepage, area of expertise)
Gian Carlo Maffettone, Scuola Superiore Meridionale

Supervisor 3 (name, contact details, homepage, area of expertise)
Konstantinos Siettos's group, University of Naples Federico II (MERC Board Member) and Scuola Superiore Meridionale

Project description (max 5000 characters)

Please include a description of the work to be carried out. State of the art, key research questions and project objectives, workplan and the methodological and application aspects of the project.

The increasing availability of autonomous agents (robots, drones, rovers) presents unprecedented opportunities for solving complex control tasks [1]. Nevertheless, these artificial systems still lack a fundamental capability observed in natural complex systems: the ability to exhibit emergent collective behavior that, arising from local interactions and transcending simple aggregation of individual dynamics, achieves precise control objectives. From killer whales coordinating to hunt schools of sardines to sheepdogs developing sophisticated patterns to control flocks, natural systems showcase how groups of agents (herders) can influence and control the dynamics of larger target populations without any centralized control. This universal class of control problems, known as 'shepherding', represents a fundamental frontier in control theory and complex systems [2]. Success in enabling artificial systems to harness such self-organized collective behavior would revolutionize critical applications: coordinating drone swarms for emergency evacuations, deploying robots to contain environmental hazards, managing complex security operations, and protecting wildlife populations through biomimetic robots. Despite nature's compelling demonstrations, no existing framework can systematically engineer such emergence while guaranteeing convergence and performance yet.

Traditionally, such frameworks have been described and used for control purposes by means of microscopic descriptions, consisting in large set of ordinary/stochastic differential equations (ODEs/SDEs), where agents, and interactions among them, are described individually [3]. Such formulations lack scalability and analytical tractability when the number of agents increases consistently. For this reason, macroscopic methodologies exploiting small sets of partial differential equations (PDEs) are gaining more and more momentum. In this context, the multitude is described as a whole, and the collective behavior is directly caught by the model, instead of being inferred from the individual dynamics [4].

Despite their inherent enhanced computational and theoretical scalability, macroscopic approaches present critical limitations with respect to their applicability in real-world scenarios. Firstly, assumptions on homogeneity of the agents' dynamics and all-to-all network topologies are considered. Then, macroscopic control solutions typically come in a centralized continuum framework, and it is crucial to develop novel methods to recast them in deployable and decentralized control inputs. Moreover, while convergence towards desired objective is typically proven in the macroscopic setting, the stability and robustness of the agent-based framework remains an important open problem.

Building upon our work on continuification control [5, 6], we will develop macroscopic control strategies for shepherding scenarios by modeling both populations using density fields through coupled PDEs. Building on our preliminary work on leader-follower density control problems [7], we will obtain strategies with provable guarantees to control the herders' density for driving target distributions toward desired configurations. Such macroscopic control strategies will be appropriately discretized into microscopic control inputs to deploy on controllable agents, by performing a thorough macro-to-micro convergence analysis. In so doing, we will leverage classic studies on two-scale convergence [8] and optimal transport [9]. In order to include topological information taking place in the continuum, we plan to rely on novel research about graphons [10], and traditional continuum Lagrangian settings commonly used in continuum mechanics [11]. Additionally, to mitigate the centralized nature often associated with macroscopic strategies, we will focus on developing decentralized control approaches using distributed algorithms.

We will validate these continuum strategies in several highly relevant applications. Specifically, we will consider shepherding and leader-followers' scenarios within the field of traffic control, collective animal behavior and swarm robotics. We will deal with the prototypical example of designing the behavior of autonomous vehicles so to smooth out traffic waves and induce desired density and velocity profiles in cars' flow [12]. Additionally, we will apply our strategies to control the density and patterns of nano-robotic swarms, influencing the collective distribution of large insect swarms for disinfestation purposes [13]. Moreover, as a testbed for our control solutions, we will consider experimental settings where large swarms of heterogenous robots plays the role of herders and targets. Such a controlled setting offers the possibility of accurately assessing the robustness and performance of our solutions.

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 tackles critical challenges at the intersection between control theory and complex systems. We plan develop a mathematical framework creating a relevant step forward both from the methodological and technological viewpoint. In particular, the development of strategies bridging the gap between the microscopic individual dynamics of agents and the macroscopic scale of emergent behaviors, is of undisputable relevance. Moreover, the

applicability of such techniques into real-world applications is a critical open problem that this project aims at.
The methodologies we plan to design finds resonance out of the applicative domains we are mainly interested in (traffic management and swarm robotics). Specifically, they can be adapted to work in contexts such as crowds' evacuation in emergency and hazardous scenarios, and environmental management (oil spillages containment).

Key references

[1]: Brambilla, Manuele, et al. "Swarm robotics: a review from the swarm engineering perspective." Swarm Intelligence 7 (2013): 1-41.

[2]: Lama, Andrea, and Mario di Bernardo. "Shepherding and herdability in complex multiagent systems." Physical Review Research 6.3 (2024): L032012.

[3]: Pierson, Alyssa, and Mac Schwager. "Controlling noncooperative herds with robotic herders." IEEE Transactions on Robotics 34.2 (2017): 517-525.

[4]: D'Souza, Raissa M., Mario di Bernardo, and Yang-Yu Liu. "Controlling complex networks with complex nodes." Nature Reviews Physics 5.4 (2023): 250-262.

[5]: Maffettone, Gian Carlo, et al. "Continuification control of large-scale multiagent systems in a ring." IEEE Control Systems Letters 7 (2022): 841-846.

[6]: Maffettone, Gian Carlo, et al. "Mixed reality environment and high-dimensional continuification control for swarm robotics." IEEE Transactions on Control Systems Technology (2024).

[7]: Maffettone, Gian Carlo, et al. "Leader-Follower Density Control of Spatial Dynamics in Large-Scale Multi-Agent Systems." arXiv preprint arXiv:2406.01804 (2024) (under review in IEEE Transactions on Automatic Control).

[8]: Allaire, Grégoire. "Homogenization and two-scale convergence." SIAM Journal on Mathematical Analysis 23.6 (1992): 1482-1518.

[9]: Chen, Yongxin. "Density control of interacting agent systems." IEEE Transactions on Automatic Control 69.1 (2023): 246-260.

[10]: Gao, Shuang, and Peter E. Caines. "Graphon control of large-scale networks of linear systems." IEEE Transactions on Automatic Control 65.10 (2019): 4090-4105.

[11]: Gurtin, Morton E., Eliot Fried, and Lallit Anand. The mechanics and thermodynamics of continua. Cambridge university press, 2010.

[12]: Čičić, Mladen, et al. "Coordinating vehicle platoons for highway bottleneck decongestion and throughput improvement." IEEE Transactions on Intelligent Transportation Systems 23.7 (2021): 8959-8971.

[13]: Sayin, Sercan, et al. "The behavioral mechanisms governing collective motion in swarming locusts." Science 387.6737 (2025): 995-1000.

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.

The student will meet on a weekly basis with at least one of the supervisors. Meetings with all the supervisors will be planned monthly and based on the project status.

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.

At least one year will be spent abroad to test, extend and validate the theoretical developments carried out within the project. Possible sites for extended periods of stay are:

KTH, Stockholm – Prof Karl Johansson's group (traffic control problems)
UC San Diego – Prof Miroslav Krstic (PDE Control)

Any other useful information

E.g., involvement of stakeholders, industrial partners, other research institutions etc, funded research projects related to the proposed activity, etc.

PRIN 22 – MENTOR Project