PhD Thesis Offer

Title: Lagrangian Micro–Macro Control of Collective Dynamics

Laboratory: Laboratoire des signaux et systèmes (L2S), CNRS, CentraleSupélec, Université Paris-Saclay, 91190 Gif-sur-Yvette, France

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I. Context

Many important systems composed of a large population of interacting agents, exhibit complex emergent **collective dynamics**. At scale, a **microscopic** description of each agent's behavior becomes intractable, motivating the use of **macroscopic** models that describe the evolution of the system state in terms of aggregate quantities. These macroscopic models, typically formulated as partial differential equations (**PDE**s), enable designing controllers that act based on the *macroscopic* state of the system, indirectly regulating the underlying *microscopic* dynamics of the system. Classical control approaches for such systems, such as boundary control [1], rely on Eulerian (fixed in space) actuation, which may be costly, sparsely deployed, or altogether unavailable. An alternative approach is to use some agents as **Lagrangian actuators**, *directly* controlling them to *indirectly* influence the macroscopic dynamics of the system via local interactions with other agents.

While macroscopic models of many types of microscopic dynamics are known [2], they often assume homogeneous agent behavior. Allowing for multiple classes of agents with distinct behaviors significantly complicates macroscopic modeling, often leading to multi-scale **micro-macro models**. The complexity of these micro-macro interactions, coupled with the Lagrangian nature of actuation, makes modeling, analyzing, and designing control for such systems an open and challenging problem, with significant potential for practical applications [3].

II. Scientific objectives

The goal of this thesis is to design model-based control laws that use microscopic **Lagrangian actuation** to affect the macroscopic dynamics of the system. The first step towards achieving this is to capture the influence that Lagrangian actuation has on the overall system, through including microscopic interactions between heterogeneous agents into the macroscopic model. This problem may be tackled analytically, applying methodologies such as **continuation** [4], or utilizing data-driven approaches such as **physics-informed neural networks** [5]. The results will be validated using trajectory data from microscopic simulations and, when available, real-world experiments. Using the macroscopic model including Lagrangian actuation, we will **quantify the achievable performance** of the closed-loop system, e.g., regarding macroscopic state reference tracking, and then design control laws specifically adapted to this system structure that achieve the control objective.

With the introduction of Connected and Autonomous Vehicles (CAVs), highway traffic flow has become a particularly compelling use case for Lagrangian micro-macro control. It will therefore be the guiding example for the work of this PhD project. Various forms of both macroscopic [6] and microscopic [7] traffic models are well known, but the interactions of vehicles with different driving behaviors are yet to be adequately macroscopically represented. The PhD student will set up microscopic and macroscopic traffic simulators, which will be used to test the modeling and control methodology and demonstrate its effectiveness. Controlling the aggregate traffic flow using multiple cooperating directly controlled CAVs within it is a central goal. The theoretical results should also be extended to other cases of large-scale multi-agent systems, e.g., pedestrian and swarm dynamics.

III. State of the art

In the context of multi-agent systems, Lagrangian actuation bears resemblance to **pinning control** [8], in the sense that a few agents (nodes) are used to influence the macroscopic (network) dynamics through local interactions with their neighborhood. A key distinction is that since it typically entails moving actuator agents through the flow, Lagrangian actuation effectively causes the **input distribution** (network structure) to change. When it comes to highway traffic, while the single-lane case is fairly straightforward, macroscopically modeling the multi-lane multi-class case, e.g., through finding its **mean-field limit** [9], is considerably more challenging, but necessary in order to implement true Lagrangian control. One extensively studied approach is to model the actuator vehicles as **moving bottlenecks**, limiting the overtaking traffic flow at their positions [3]. However, this typically assumes that the actuator vehicle is acting in isolation, and collaborative Lagrangian actuation, where multiple agents act together to exert more control over the macroscopic state than they would be able to do alone, has only been partially addressed in the simplest case of multi-lane controlled platoons [10]. This project aims to formulate a more generic approach for building macroscopic models that are conducive to **Lagrangian control** design, and then exploit them for regulating the **macroscopic collective dynamics**, providing **performance guarantees**.

IV. Required skills

The candidate should have a strong background in engineering, applied mathematics, or a related field (Grandes Ecoles or Master), focusing on dynamical systems and control. Good written and oral communication skills in English are required. Experience with research, numerical simulation, and data-driven modeling will be considered an asset. Prior exposure to modeling and simulation of road traffic is welcome but not mandatory. The PhD can be preceded by a research internship at the lab.

V. Application

To apply, send an email with your CV to Mladen Čičić: `mladen.cicic@centralesupelec.fr`.

References

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