Collective Motions of Animals and Robots
May 27-31, 2024 Cargèse Frances

Short oral presentations

Monday

Candelier Raphaël
Laboratoire Jean Perrin, Sorbonne Université, Paris
France

Collective motion of agents driven by simple artificial neural networks

Artificial neural networks are a promising framework for modeling animal behavior and driving robot swarms. Here we study simple 2D agents with radial perception, fixed velocity and the ability to turn and show that even with a single-neuron driving ANN a large variety of behaviors can emerge, comprising static and oscillatory patterns, due to the coupling between the neural network's dynamics and the collective motion. These systems can both fit a large panel of field data to reproduce natural behaviors and be submitted to diverse simulation protocols to be studied like active matter. Due to the very specific nature of the visual interaction (asymmetric, non-reciprocal, long range), several differences and “non-physical” effects can be observed with respect to force-driven systems like assemblies of colloids. The model can be extended to multi-species interactions, and be used to simulate a mixing-demixing phase transition with a bistability regime, predator-prey or rock-paper-scissors dynamics for instance. Finally, when fixed spatial constraints are imposed these systems display a great level of adaptation and are able to find specific paths in mazes, which is a remarkable example of collective intelligence considering the elementary nature of both the internal driving (single-neuron decision network) and the inter-individual communication (bleary visual interactions).

Chervanyov Alexander
University of Münster,
Germany

Kinetic model of the static and dynamic patterning in the system of self-propelled agents.

The self-propelled agents (SPP) are often used as a workhorse model of the collective motion of such bio-systems as bacterial colonies, fish schools, bird flocks, to name a few. The reported work looks into the formation of steady non-equilibrium (moving and resting) states of the SPP undergoing the competitive processes of the Turing patterning, rotational relaxation and rotational diffusion of the SPP self-propulsion velocities. The developed kinetic model predicts several non-trivial steady states of the SPP system. The transitions between these states are caused by the intricate interplay among the involved effects of the pattern formation, orientational order, and coupling between the SPP density and orientation fields. In its non-equilibrium steady state, the patterns of SPP are shown to exhibit collective motion with the constant velocity predicted by the model. As a main result of the reported study, the transition between the resting and moving non-equilibrium steady states of the SPP system are quantitatively explained by rationalizing the primary and secondary instabilities experienced by this SPP system. The obtained analytical results show excellent agreement with the performed rigorous numerical simulations.

Choudhury Udit
Indian Institute of Technology – Roorkee
India

Collective behavior of light-driven microrobots- a rheological perspective

Micro-robots are colloidal analogues of bacteria, that demonstrate self-propulsion in fluids. Recent experiments have demonstrated that dense suspensions of colloidal micro-robots(active colloids) show interesting collective phases.1,2 Collective behavior of active entities in fluid influences the rheological properties of colloid-fluid suspension. Pioneering observations of activity driven change in rheological

properties in bacterial baths and actin-motor protein suspension,3,4 have motivated researchers to study rheological properties of synthetic “active” colloidal suspensions.
Here, we developed a synthetic active colloidal suspension of light-driven microrobots. Individual units consist of shape-anisotropic colloids, enabling self-propulsion at low densities. At higher densities, we observed the system to evolve to an arrested network like phase, that can be optically tuned. The active opto-rheological suspension was characterized with both micro and bulk rheological measurements which confirms light controlled change in effective viscosity due to activity in the suspension.5,6 We will also report our recent advances in understanding the rheological properties of this active colloidal suspension with differential dynamical microscopy technique.
Ref – 1.Palacci J.et al Science(2013) 2. Bricard A. et al. Nat. Commun(2015).3.Lopez H. et al Phys. Rev. Lett. (2015) 4. Koenderink et al PNAS (2009)5.Singh,D.P et al. Adv. Mater(2017) 6.Choudhury, U. et al Adv. Mater.(2019).

Costello Luke
Max Planck Institute of Animal Behavior Konstanz
Germany

Locust Collective Behavior at Large(r) Scales

One of the most exciting directions in active matter research has been the possibility of bridging our physical understanding of nonliving matter with that of living systems (or living matter). Considerable progress has been made on theoretical aspects of active matter but making connections to actual living systems has been limited in part due to a lack of available data. Typically lab experiments involving swarms of living agents have been restricted to small organisms (often microorganisms) or small system sizes relative to natural scales. We seek to fill this gap using the desert locust (Schistocerca gregaria) as a model system. We recently conducted a set of experiments with up to 10000 juvenile (flightless) locusts marching in a 5m diameter arena. These experiments were run over a few different densities, with different behaviors observed across the range. I plan to present the results of this experiment, along with some preliminary analysis.

Tuesday

Davis Luke
Isaac Newton Institute, Cambridge
UK

Active Matter under Control: Insights from Response Theory

Active constituents, including animals and robots, burn fuel to sustain individual motion, giving rise to collective effects that are not seen in systems at thermal equilibrium, such as phase separation with purely repulsive interactions. There is a great potential in harnessing the striking phenomenology of active matter to build novel controllable and responsive materials that surpass passive ones. Yet, we currently lack a systematic roadmap to predict the protocols driving active systems between different states in a way that is thermodynamically optimal. Equilibrium thermodynamics is an inadequate foundation to this end, due to the dissipation rate arising from the constant fuel consumption in active matter. Here, we derive and implement a versatile framework for the thermodynamic control of active matter. Combining recent developments in stochastic thermodynamics and response theory, our approach shows how to find the optimal control for either continuous- or discrete-state active systems operating out of equilibrium. Our results open the door to designing novel active materials that are not only built to stabilize specific nonequilibrium collective states but are also optimized to switch between different states at minimum dissipation.

Ding Serena
Max Planck Institute of Animal Behavior, Konstanz
Germany

Collective behaviour of nematodes

C. elegans has recently emerged as a model for several striking collective behaviours such as aggregation, wurmuration, towering, and network formation. Combining the powerful experimental accessibility of this major lab model organism with the knowledge that collective phenomena are widespread and highly relevant for many nematodes, we exploit different nematode species to understand how and why they behave collectively. Through several thematically related projects that I will introduce, we seek to dissect the proximate mechanisms of nematode collective behaviour using tools from quantitative behavior and modelling, as well as integrating fitness measurements to demonstrate the function of collective behaviour in ecologically relevant nematode groups.

Duclut Charlie
Sorbonne Université, Paris
France

Stochastic dynamics of chemotactic colonies with logistic growth

The interplay between cellular growth and cell-cell signaling is essential for the aggregation and proliferation of bacterial colonies, as well as for the self-organization of cell tissues. To investigate this interplay, we focus here on the collective properties of dividing chemotactic cell assemblies by studying their long-time and large-scale dynamics through a renormalization group approach. Our analysis reveals that a novel effective chemotactic interaction -- corresponding to a polarity-induced mechanism -- is generated by fluctuations at macroscopic scales. This term, usually overlooked in phenomenological approaches, emerges from the interplay of the well-known Keller-Segel chemotactic nonlinearity and cell birth and death processes. Its consequences on the critical dynamics will be discussed.

Forkosh Oren
The Hebrew University, Rehovot
Israel

Equilibrium states of spherical cows: Herd Dynamics, Spatial Organization, and Information transfer

This study offers a comprehensive examination of the intricate dynamics and spatial arrangements within cow herds, particularly focusing on their natural tendency to form spherical configurations during rest, which serve crucial roles in predator deterrence, efficient foraging, and nurturing of offspring. Employing a bespoke tracking system, we tracked the precise positions of each of the 60 cows within a dairy herd over months, with a high spatio-temporal resolution (30 cm at 1 Hz). Our investigation unveils the presence of individualized attraction zones among cows, leading to a diffusion of those with larger zones towards the periphery of the herd. This spatial distribution enhances the collective information processing capabilities of the herd, facilitating swift and cohesive responses to environmental stimuli. Furthermore, the study delves into the influence of various factors such as social hierarchy, health status, stress levels, and age on the social forces dictating each cow's position within the herd. The findings offer profound insights into the social structures and movement patterns inherent in cow herds, elucidating the mechanisms governing their spatial organization and equilibrium states.

Wednesday Morning

Hua Hoa-Ai Béatrice
University of Liege
Belgium

Jamming transition in robotic active tissues

Recently, attention has risen on collective behavior in active matters with a particular emphasis on understanding novel kinetic phase transitions observed in biological systems. The cell jamming transition has been the subject of much research since it is useful in identifying living tissue processes such as cancer invasion. Using centimeter-size vibrobots to activate flexible membranes within confined space, we study a synthetic macroscopic system aiming to capture the physical components of the jamming observed on biological tissues. Through a combination of experimental observations and simulations, we analyze mean square displacement and shape changes of cells, with a focus on the impact of cell density, membrane rigidity, and robot motility on the jamming limit knowing that those three parameters can be connected to biological processes. By exploring whether synthetic active matter experiments yield analogous observations to those in living systems, our goal is to establish an optimized experimental setup wherein parameters are precisely controlled. This refined setup enables the investigation of complex microscopic phenomena such as cell segregation and self-organization. I will present our progress in identifying the minimal physical ingredients required to accurately describe and replicate cell jamming. Our research endeavors to discern dominant mechanisms, offering clarity on the intricate correspondence between biological processes and physical parameters.

James Martin
University of Genoa
Italy

Swimming mode determines how well mesoscale swimmers shield their odor in turbulence

Odor transport in turbulent environments is a complex phenomenon of broad scientific interest. In aquatic ecosystems, understanding odor transport is critical to elucidating the mechanisms behind ecological processes. However, despite potential significance, how the hydrodynamic fluctuations introduced by the swimmers couple with odor dispersion remains unexplored.

In this talk, we explore the coupling of chemical and mechanical signals from mesoscale swimmers (Reynolds number <= 50), immersed in a turbulent open channel flow. We consider a collection of such swimmers, varying their Reynolds numbers and evaluating the consequential changes in odor distribution. We show that the velocity fluctuations due to the swimmers play a significant role in changing the range and distribution of odor signals by screening the intensity and fluctuations of odor distribution downstream. Furthermore, there are substantial differences in screening depending on whether the swimmers are pushers or pullers, with pullers being more effective at screening their odor from predators.

Our findings provide valuable insights into the coupling of mechanical and chemical signals of mesoscale swimmers in turbulence with novel considerations regarding the evolutionary preferences of specific swimming modes.

Jarrahi Mojtaba
Université Paris-Saclay - Orsay
France

Mixing by Phototactic Oscillatory Motion of Algae

Recent studies suggest that bioconvective patterns naturally developed in suspensions of motile microorganisms at high concentration may provide biomixing. In this work we report a study of the phototactic response of Chlamydomonas reinhardtii to induce biomixing in a small bioreactor at macro-scale. By exploiting the phototactic mechanism, we stimulated the microalgae to swim in opposite directions repeatedly in cycles of 40 min (20′ left, 20′ right) in the photobioreactor. The resulting Phototactic Oscillatory Motion (POM) lasted 7 days
and maintained an amplitude close to the width of the bioreactor. Phototaxis allowed algae to remain in suspension without the use of any mechanical stirring system. We have demonstrated that light can be controlled to effectively provide mixing and ensure access to nutrients in form of an oscillatory motion at no extra energetic costs. This strategy can replace mechanical agitation in the manner of a ‘phototactic stirring’ under certain circumstances in pursuit of energetic sobriety.

Jung Gerhard
Université Grenoble Alpes, Grenoble
France

From decentralized learning of social agents to emergent behavior in heterogeneous environments

Adapting individual behavior of agents, be they animals or robots, to accomplish intricate collective tasks poses significant challenges. In the realm of machine learning, addressing such complexities often involves resorting to genetic algorithms, where a central omniscient machine seeks the optimal collective solution. However, in natural systems, individual agents must adapt their behavior through decentralized processes, striving to optimize personal rewards.

In this presentation, I will elucidate our approach to tackling this problem by leveraging tools from statistical physics, grounded in a minimalist framework: the Vicsek model for active matter. Through numerical simulations, we explore how individual agents attempt to optimize their behavior within increasingly heterogeneous environments. The introduction of heterogeneity introduces 'frustration', amplifying the difficulty of attaining optimal solutions. Additionally, I will discuss preliminary findings concerning the adaption of a group of agents to changing environments. These findings mark an initial step towards enhancing our comprehension of emergence and collective behaviors within systems composed of complex agents, approached from the generic perspective of statistical physics.

Wednesday Afternoon

Levay Sara
Universidad de Navarra, Pamplona
Spain

Experimental and numerical study of the collective behavior of macroscopic light-driven active particles

Aiming to answer questions related to the collective behavior of active matter, we created novel, macroscopic self-propelled agents excited by light. In our experimental system, we use small robots called HEXBUGs, with photovoltaic cells mounted on their top, so their behavior is tuned by changing the illumination intensity. Thus, the activity of the internally excited agents is externally controlled, a common concept in microscopic systems but pioneering in experiments with macroscopic particles. Our fully controllable illumination panel allows us to change the illumination intensity spatially and temporally, so we can impose both spatial and temporal gradients and analyze the response of the system by analyzing the diffusion, mixing, and clustering of the particles.
First of all, we present the clustering behavior of the agents under homogeneous illumination intensities. Clusters of different sizes develop but their formation, duration, and dissolution depend on the intensity and the particle density in the system. Lower intensities, thus slower agents tend to form larger and more stable clusters. In cases with small particle density, the clusters are not stable in the sense that they dissolve relatively quickly, while higher density facilitates the creation of stable clusters that cannot be easily destroyed at a given level of particle activity.

Liang Li
University of Konstanz,
Germany

Schooling fish: from biology to robotics and back

With over half a billion years behind them, fish have evolved to swim with remarkable efficiency, agility, and stealth in their three-dimensional aquatic world. Given this, it's natural that engineers often look to fish for inspiration when developing efficient underwater propulsion systems. Over the years, roboticists have been inspired by these biological marvels to design fish-like robots that mimic real fish in terms of morphology, locomotion, movement, and hydrodynamics. Interestingly, the trend has recently shifted from merely drawing inspiration from biology to using robotics as a tool for better understanding biological processes. In this talk, I will first discuss our approach to designing and controlling these robotic fish, rooted in the concept of bio-inspiration. I will then provide examples of how we use both real and virtual robots to explore the mechanisms of collective behavior in schooling fish. To conclude, I'll offer a glimpse into my current and future endeavors in the realms of robotics, hydrodynamics, and biology.

Thursday

Loisy Aurore
IRPHE – Marseille
France

From active matter to smart matter: learning collective navigation

Collective navigation is the ability, for a group of agents, to cooperate in order to move coherently toward a target. Here we consider the problem of reaching a hidden target emitting a chemical substance that disperse in the environment. While there exists a mean gradient that points toward the source, dispersion (e.g. by a flow) creates a complex concentration landscape with multiple local maxima away from the target. In this situation, agents that simply follow local concentration gradients (a behaviour known as chemotaxis) will inevitably fail. To be able to reach the target, agents must cooperate. We consider Vicsek-like self-propelled particles able to sense the local concentration and train them at locating the source using multi-agent reinforcement learning. The discovered emergent cooperation strategies may shed some light on how living entities navigate in their natural environment and may serve as an inspiration for swarm robotics.

Moretto Pierre
Université Paul Sabatier, Toulouse
France

Collective Load Carrying

Humans and ants serve as biological models for collective load carrying, but can they be considered good models for cobotics, i.e., collaborative robots? We conducted experiments at both scales using 3D biomechanics to assess the dynamics of a system involving two humans or four ants and the load they carry. At this stage, we can analyze the synergies within the poly-articulated system by computing joint constraints and moment forces. This allows us to calculate energy transfers between segments and the carried load. These parameters help us discretize functions that emerge based on the load weight, revealing individuals guiding while others provide support. These synergies, observed at individual and inter-subject levels, explain the efficiency of contributors and behaviors that prioritize individual safety and overall transport efficiency. Constraint sharing increases with the weight of the carried load, leading to alignment of actions. At the ant scale, estimates show less discretization among individuals, not excluding the pattern organization can be based on ant proprioception.
Cobotics faces a challenge in decision-making to emulate different behaviors based on information perceived by the machine from its sensors and proprioception. This must occur in real time, with the possibility of anticipation based on partner movements.

Mullick Pratik
Wrocław University of Science and Technology
Poland

Algorithms to detect emerging patterns in collective motion of humans

The collective motion of social agents arising from their interactions has been the subject of intense scientific research. Understanding the collective dynamics of human crowds is crucial for improving pedestrian traffic flow, ensuring crowd safety, effective urban planning, and preventing crowd disasters. Analyzing crowd dynamics and pattern formation in human data is a crucial first step toward successful human-crowd modeling. When two streams of pedestrians cross at an angle, striped patterns spontaneously emerge due to local pedestrian interactions. Such spontaneous pattern formation is an example of self-organized collective behavior, a topic of intense interdisciplinary interest. In this talk, I wish to present numerical strategies developed to study the geometric properties of striped patterns that arise as a consequence of two crossing flows. We introduced two novel algorithms for analyzing striped patterns in pedestrian data: (i) an edge-cutting algorithm, which detects the dynamic formation of stripes and allows us to measure local properties of individual stripes; and (ii) a pattern-matching technique, based on the Gabor function, which allows us to estimate global properties of the striped pattern at a given time. We found an invariant property: stripes in the two groups are parallel and perpendicular to the bisector at all crossing angles. I would also like to present our recent work, where we improved the accuracy of the pattern-matching technique by changing the underlying optimization algorithm.

Nayebi Aran
Massachusetts Institute of Technology.
USA

A relationship between predictive neural models and high-dimensional embodied control

I will present two case studies demonstrating a relationship between building artificial neural networks that are highly predictive of biological neural activity in rodent and primate brains, and their ability to best control a high-dimensional virtual animal body compared to alternative methods.

The first case study (Nayebi*, Kong* et al. 2021) is in mouse visual cortex. Here we build the most quantitatively accurate models of the mouse visual system by identifying the computational features different from those of the primate visual system needed to capture neural responses across mouse visual areas. In particular, we find that models trained with self-supervised, contrastive algorithms were able to capture the most variance in the neural responses across all visual areas – much more so than more specialized, supervised objectives. By “implanting” the supervised and contrastive visual networks into a biomechanically-validated virtual rodent body of Merel*, Aldorando*, Marshall* et al. 2020, we observe that the contrastive model was better able to transfer to the novel maze environment, shown
by its ability to obtain more reward across multiple episodes. Our results illustrate how the mouse visual system can be interpreted as a resource-limited system that has a comparative advantage in self-learning a task-general visual representation.

The second case study (Nayebi et al. 2023) is related to mental simulations in primates. Specifically, we construct and evaluate several large classes of sensory-cognitive networks to predict the future state of rich, ethologically-relevant environments. Notably, self-supervised models that future predict in the latent space of video foundation models that are optimized to support a diverse range of sensorimotor tasks, reasonably match both human behavioral error patterns and neural dynamics across all environmental scenarios that we were able to test. Overall, our findings suggest that the neural mechanisms of primate mental simulation are thus far most consistent with being optimized to future predict on dynamic, reusable visual representations that are useful for embodied AI more generally.

Friday

Saintyves Baudouin
University of Chicago
USA

A self-organizing robotic aggregate using solid and liquid-like collective states

Designing robotic systems that can change their physical form factor as well as their compliance to adapt to environmental constraints remains a major conceptual and technical challenge. To address this, we introduce the Granulobot, a modular system that blurs the distinction between soft, modular, and swarm robotics. The system consists of gear-like units that each contain a single actuator such that units can self-assemble into larger, granular aggregates using magnetic coupling. These aggregates can reconfigure dynamically and also split into subsystems that might later recombine. Aggregates can self-organize into collective states with solid- and liquid-like properties, thus displaying widely differing compliance. These states can be perturbed locally via actuators or externally via mechanical feedback from the environment to produce adaptive shape-shifting in a decentralized manner. This, in turn, can generate locomotion strategies adapted to different conditions. Aggregates can move over obstacles without using external sensors or coordinates to maintain a steady gait over different surfaces without electronic communication among units. The modular design highlights a physical, morphological form of control that advances the development of resilient robotic systems with the ability to morph and adapt to different functions and conditions.

"A self-organizing robotic aggregate using solid and liquid-like collective states." Baudouin Saintyves, M. Spenko, H. M. Jaeger. Science Robotics (2024)

Ventéjou Bruno
Université Grenoble Alpes, Grenoble
France

A hydrodynamic toy model for fish locomotion

The social interaction of fish has been mainly studied in 2D without hydrodynamic interactions [1,2] or with hydrodynamic interactions in the limit of the far-field [3]. As a fish swims, it affects the flow around its body in a complex manner at distances much larger than the typical fish scale. Thus, it could compete with cognitive interaction. Some efforts have been done to describe precisely the flow generated around a fish [4,5]. But, the high cost of hydrodynamic simulations prevents the use of such models to study schools of fish.
We propose a toy model, that is able to generate the vortex wake induced by the fish locomotion and which is light compare to solving the fish tail flapping. We describe the fish as a rigid body by a penalty method and achieve the description of the tail flapping by exerting a torque in the fluid compensated in the body. The trajectory of the fish is determined by the position of the tail in relation to the body. We perform a full characterization of the toy model and compare it to the scaling found in the animal kingdom [6].

[1] J. Gautrais, et al., J. Math. Biol. 58, 429–445 (2009).
[2] D. S. Calovi, et al., NJP, 16(1) (2014).
[3] A. Filella, et al., Phys. Rev. lett. (2018).
[4] M. Bergmann, et al., Bioinspiration & biomimetics (2014).
[5] G. Novati, et al., Bioinspiration & biomimetics, (2017).
[6] M. Gazzola, et al., Nat. Phys. (2014).

Verma Siddhartha
Florida Atlantic University
USA

Emergent behavior of autonomous group swimmers using multi-agent deep reinforcement learning

It has been shown that various fish species can utilize the velocity field generated in the wakes of obstacles, and in the wakes of other swimmers, to reduce their energy expenditure. Here, we explore the hydrodynamic benefits of group swimming using two-dimensional numerical simulations of self-propelled anguilliform swimmers, coupled with multi-agent reinforcement learning. These artificial swimmers utilize a sensory input system that allows them to detect the velocity field and pressure on the surface of their body, which is similar to the lateral line sensing system. Deep reinforcement learning is used as a tool to discover optimal swimming patterns at the group level, as well as at the individual level, as a response to different objectives and flow fields. This can be useful in distinguishing various swimming patterns and their role in achieving higher speeds or efficiency, which are desirable objectives in different scenarios. The adaptations in response to changes in the surrounding flow field are also examined by training the swimmers in stationary flow, as well as uniform flow. These flow fields are representative of conditions encountered by fish in lakes and oceans (stationary flow), as well as during long-distance migration and in rivers (uniform flow). The physical mechanisms revealed can be helpful in understanding the motivation behind different swimming behaviors from a hydrodynamic and energetics standpoint.
