MERC PhD Project Proposal 2022/2023

Title of the research project:

Emergent energetic regulation in dynamic biological networks

Keywords (up to five)

Collective behavior, clonal raider ant, dynamical systems, time-series analysis

Supervisors (at least two from two different areas):

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Project description (max 5000 characters)

Energetics has not always been central to understanding the evolution and functioning of living systems, often taking a back seat to advances in molecular biology and population genetics. While a significant portion of biological and biochemical research is dedicated to the mechanisms by which organisms acquire, transform, store, and release energy, theoretical perspectives on how these processes are integrated across levels of biological organization have rarely been proposed. Central to this question is the concept of ***energetic regulation***, which is the ability of a biological system to maintain the tradeoffs between energy inputs and outputs within bounds that are compatible not only with its survival and functioning but also with the production of the next generation. Indeed, while maximizing energy conversion may be the ultimate product of biological evolution, it is also constrained by physical limits to the integrity of organisms. For instance, the rate of heat dissipation imposes an upper limit to the metabolic rate of an organism. On the other hand, there are many biomechanical and ecological benefits to evolving a larger body size. Hence, more massive organisms must maintain lower metabolic rates relative to that of smaller organisms or, alternatively, evolve dynamic control over their metabolism, enabling them to sense and adaptively respond to changes in their size and environment.

The overarching objective of the proposed project is to understand ***how collective systems, made of many loosely connected units, achieve energetic regulation and maximize the efficiency of energy conversion towards an objective.*** The specific questions that we aim to address can be grouped into three categories, pertaining to energy regulation, its principles, and its consequences:

1. Interactions within the colony and the colony-scale energy regulation they control, e.g., what is the relative role of touch and pheromone sensing on the group response? Do they beget similar or different interaction network structures? What is the saliency of each of these cues with respect to energy regulation?
2. Interactions between the colony and its physical and social environment, e.g., how do some individuals decide to begin or terminate foraging for the colony?
3. Colony adaptations to achieve energy regulation, e.g., can the foraging problem be formulated in terms of an energy functional to be optimized and what are the roles of social interactions and the colony's environment in this minimization?

The supervisors and student will address these questions through a synthesis of data-driven inference and mathematical modeling. Experiments will be conducted by biologist collaborators in New Jersey Institute of Technology and Providence College, USA, using clonal raider ants *Ooceraea biroi.* This model organism reproduces clonally (so that all individuals in a colony are genetically identical) and alternates between statary phases (during which they lay new eggs and do not leave their shelter) and foraging phases (during which they exhibit high levels of activity).

We plan to anchor the work in temporal networks, advancing robust, statistical approaches for distinguishing irreducible from reducible links using measurements of interactions over time. Reducible interactions pertain to node-specific properties, while irreducible interactions reflect dyadic relationships between nodes that form the persistent network structure. That is, reducible links may be those given by random contact with ants in the colony, whereas irreducible ones pertain to links between individuals with the same roles in the colony such as foraging or nursing the larvae. The mechanism by which individuals differentiate into these roles (which determines the colony's generation and consumption of energy) is not well understood, and it may depend on age or location relative to tasks to be performed, which are testable hypotheses. Specifically, the student will (i) track temporal contacts between ants in the experimental data (taking into account the time-varying and spatial nature of pheromone-based versus tactile interactions); (ii) assemble these results into a network encompassing multidimensional interactions; and (iii) filter links from this network to disentangle irreducible from reducible links and to measure the relative strength of the two communication pathways the ants use. Once the multilayer interactions networks are identified from data, we will investigate their properties as functions of the factors that are varied over the experimental campaign. Insights from the network structure will be used to define a dynamic model of the colony in the form of coupled stochastic differential equations, which includes the arousal and foraging behavior of a single individual ant and the influence between colony members. Simulations of the model will be used to inform swarm robotics control schemes in collaboration with the roboticist on the team.

Relevance to the MERC PhD Program (max 2000 characters)

This projects ideally fits the interdisciplinary spirit of the MERC PhD program. The participating student will have the opportunity to follow the research question of collective energetic regulation from the inspiring biological system to the ultimate application in swarm robotics. The supervisors' expertise spans dynamical systems, time-series analysis, and network analysis, and their collaborators on the project include two biologists (Simon Garnier and James Waters from New Jersey Institute of Technology and Providence College, respectively) and a roboticist (Michael Rubenstein from Northeastern University) with whom the student will be encouraged to interact. The student will be guided through the challenges of interdisciplinary research, learning how to cope with the different languages and tools used across the disciplines. Moreover, the two US host institutions (New York University and Virginia Tech) will give the student experience at a range of different settings, from a private university on an urban campus to a public university in a rural location.

The mathematical and statistical tools upon which the project is based are at the frontier of knowledge in complex systems, thereby offering an invaluable learning basis for students and an empowering opportunity to contribute to the state of knowledge. Dynamical systems, network science, time-series analysis have a central role in the proposal and are topics that fit well with the training and curricula of the PhD program.

Key references

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- Nadini, M., Rizzo, A. & Porfiri, M. Reconstructing irreducible links in temporal networks: which tool to choose depends on the network size. J. Phys. Complex. 1, 015001 (2020) doi:10.1088/2632-072X/ab6727.
- Zino, L., Rizzo, A. & Porfiri, M. Continuous-time discrete-distribution theory for activity-driven networks. Phys. Rev. Lett. 117, 228302 (2016) doi:10.1103/PhysRevLett.117.228302.

Joint supervision arrangements

The supervisors are long-time friends who are already beginning work on this project. The student is expected to reside at each host institution for approximately half of their time abroad, with the exact timing and distribution of visits left to planning between the student and supervisors. We note that a train travels between New York and southwest Virginia twice per day and there are several direct flights per day between the two sites.

The exact frequency of meetings with the supervisors will depend on the needs of the student and the stage of the work, but we expect that the on-site supervisor will meet the student 3-4 times per week, while the off-site supervisor may be in touch weekly using a videoconferencing software. We anticipate that there may be periods when meeting twice per month with both supervisors will be sufficient, for instance, when the student is learning and studying some methodology or the state of the art, and other periods when one-on-one meetings with any of the supervisors should happen two or three times per week, for example, when dealing with the development of new models or algorithms. The student will also be expected to participate in monthly meetings with the interdisciplinary research team working on this research project.

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

The New York University (NYU) Tandon School of Engineering is the engineering and applied sciences school of NYU. Tandon is the second oldest private engineering and technology school in the United States. Located in the Brooklyn Tech Triangle, ten minutes walking to the Brooklyn Bridge and connected with subway to NYU or any of the other NYU schools in the City. Prof. Porfiri is an Institute Professor (the highest distinction at NYU Tandon), with tenured appointments in Biomedical Engineering and Mechanical and Aerospace Engineering. Prof. Porfiri is the Director of the Center for Urban Science and Progress (CUSP), a unique NYU research ceter created in partnership with New York City for interdisciplinary application of science, technology, engineering, and mathematics in the service of urban communities across the globe. Prof. Porfiri's laboratory, the Dynamical Systems Laboratory (DSL), was founded seventeen years ago with the vision of creating an interdisciplinary space with fundamental research in dynamical systems with clear societal impact. The laboratory is housed between CUSP and the Department of Mechanical Engineering. MERC students joining the project will have office space in the newly renovated CUSP building and access to any of the DSL facilities. At the DSL, they will be fully integrated in any of the lab activities, such as seminars, workshops, focused courses for professional development, and collaborative efforts within and outside the group.

Virginia Tech is one of the US's land-grant institutions established with funds from the 1862 Morrill Land-Grant Act, which created public universities specializing the agriculture and the mechanical arts in each state. The university is located on a scenic 2.600 acre campus in Blacksburg, a college town in the beautiful Appalachian mountains of southwest Virginia. The student population is approximately 34.000 individuals, and resources abound on the campus, including libraries, numerous regular seminar series, and laboratory facilities. Prof. Abaid is an associate professor in the Department of Mathematics, who directs a lab comprising graduate students in mathematics and engineering mechanics and who is active in the flourishing mathematical biology community in her department. MERC students joining the project will have office space and access to lab space, as well as opportunities to build professional relationships within the faculty and student body.

Ideally, the student would spend 24 months between New York and Virginia to ensure ample opportunities for training and full integration with the supervisors' research teams. How to split the time between NYU and Virginia Tech will be discussed based on student preferences; we also anticipate that, under normal circumstances, Profs. Porfiri and Abaid will visit each other's institutions regularly, and Prof. Porfiri to visit MERC, throughout the Summer term and the Winter break.

Any other useful information

Ants are not humans, but the overall mechanisms of energetic regulation is paralleled by urban scaling in large cities, with respect to their socioeconomic output and built environment. In this vein, a lot of the knowledge that will be developed in this project finds parallels and motivations in urban science, the core of CUSP. Using NYC as a living laboratory, CUSP contributes foundational knowledge and novel technologies for increasing our understanding of urban processes and solving complex urban problems, from ensuring the health and wellness of urban populations, to making our cities more accessible and inclusive, to supporting local governments to be more responsive to citizens' needs. CUSP members include faculty and researchers from computer and data science; civil, electrical, biomedical, and mechanical engineering; human-technology design and interaction; applied mathematics and statistics; public health and policy; and the social sciences. CUSP has a large number of ongoing partnerships with city agencies, non-profits, industry, academic organizations, and start-ups that will provide project-based internship opportunities for trainees. These convergent research activities and synergistic connections with NYC put CUSP at the forefront of fundamental and applied research in urban accessibility, a priority of NYC's administration. CUSP runs and Interdisciplinary Doctoral Track, which, like MERC, offers a collaborative environment for excellence in interdisciplinary research. MERC students will be integrated in doctoral activities at CUSP, thereby promoting collaborations with other junior researchers.

Profs. Porfiri and Abaid are two of the co-principle investigators of a newly funded National Science Foundation Project on collective energetic regulation in clonal raider ants, which brings together researchers from five US universities, including Tandon/NYU and Virginia Tech. MERC students will be welcomed into the large, interdisciplinary group working to understand this problem, which ranges from experts in physiology and animal behaviour to swarm roboticists. In addition to meetings with their supervisors on their research project, MERC students will participate in group meetings, attend lectures and seminars, and be encouraged to collaborate directly with other team members if interest and time allow.

Please return this form via email by no later than 24th February 2023