MOVING WITH MINIMUM EFFORT - OPTIMAL WORK PROTOCOLS FOR SYSTEMS WITH HIDDEN DEGREES OF FREEDOM

Sarah A.M. Loos[1,2]

[1]DAMTP, Centre for Mathematical Sciences, University of Cambridge, Cambridge, United Kingdom
[2]Max Planck Institute for Dynamics and Self-Organization, Goettingen, Germany

ABSTRACT

The framework of stochastic thermodynamics provides powerful tools to quantify entropy flows, dissipation, and efficiency in small-scale processes as fluctuating quantities. A key open challenge arises when memory effects are introduced by hidden degrees of freedom that evolve on comparable timescales but remain inaccessible to direct measurement or control. Such memory naturally emerges, for instance, when the system of interest is coupled to a complex fluid with internal relaxation dynamics.

In this talk, we address the impact of memory on thermodynamically optimal control. As a paradigmatic case, we consider the problem of dragging a particle in a harmonic trap through a fluid, over a prescribed distance within a fixed time, while minimizing the average work input. For passive particles in viscous media, the optimal protocol is known to consist of two symmetric jumps at the beginning and end of the trajectory [1]. We analytically demonstrate—and experimentally confirm using colloids in optical tweezers in both viscous and viscoelastic fluids—that this feature originates from an underlying time-reversal symmetry of the optimal control problem [2]. Strikingly, we can show that symmetry holds universally for all media described by a linear generalized Langevin equation, irrespective of the specific memory kernel or noise correlations, encompassing glassy, granular, and active systems [3; 4]. Our findings thus provide both a general criterion for identifying optimal protocols and a practical strategy for constructing them.

Keywords: stochastic thermodynamics, optimal control, non-Markovian dynamics, generalized Langevin equations

REFERENCES

[1] T. Schmiedl, U. Seifert, *Optimal Finite-Time Processes In Stochastic Thermodynamics*, Phys. Rev. Lett. **98**, 108301 (2007).
[2] S. A.M. Loos, S. Monter, F. Ginot, and C. Bechinger, *Universal Symmetry of Optimal Control at the Microscale*. Phys. Rev. X **14**, 021032 (2024).
[3] R. Garcia-Millan, J. Schüttler, M. E. Cates, and S. A.M. Loos, *Optimal Closed-Loop Control of Active Particles and a Minimal Information Engine*. Phys. Rev. Lett **135**, 088301 (2025).
[4] J. Schüttler, R. Garcia-Millan, M. E. Cates, and S. A.M. Loos, *Active particles in moving traps: Minimum work protocols and information efficiency of work extraction*. Phys. Rev. E **112**, 024119 (2025).