OPTIMAL BIO-LOCOMOTION STRATEGIES IN FLUIDS

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EXECUTIVE SUMMARY

Is the familiar goldfish hiding a technological treasure? Seemingly simple, its wandering around a bowl involves complex interactions among its senses, its body, and the surrounding water. More generally, during millions of years of evolution animals have refined their shapes, gaits, and collective behaviors to master the complex interplay among their bodies, their senses, and the environment. How can we understand the biophysical mechanisms at play and translate them into rational design principles? To inquire into the fundamental mechanisms underlying swimming and flying we have developed an automated inverse design method based on large-scale numerical simulations and artificial intelligence techniques. This allows us to set a desired trait—for example, energy efficiency—and to reverse engineer corresponding optimal solutions. Subsequent computational analysis guides our theoretical intuition toward the identification of broader design principles.

RESEARCH CHALLENGE

All animals that swim or fly are constantly confronted with the physics of the surrounding media. Whether natural creatures can take advantage of physics to push their performance limits depends on their biological strategies, from materials, morphologies, and gaits to collective behaviors. Their struggle for survival has produced a rich array of solutions that often outperform human engineered designs and that work in ways we still do not fully understand. They bear a great potential for technological innovation, with applications ranging from robotics to energy-harvesting devices.

In this context, bioinspired approaches rely on mimicking existing natural solutions to enhance the performance of current engineered designs. Nevertheless, one may question to what extent engineers should follow biomimicry. Indeed, natural creatures have not evolved to optimize engineering objectives, and we have limited information to determine whether a particular solution optimally serves a given function. Moreover, today's materials and components pose constraints and enable opportunities that may differ from their biological counterparts. Hence, we suggest that man-made solutions obtained through inverse design based on an automated optimization process may outperform pure biomimicry.

METHODS & CODES

The characterization of biopropulsion, from the standpoint of optimality, demands accurate, robust, fast, and flexible numerics for flow-structure interaction problems. We have been developing and implementing novel schemes for the direct numerical simulation of individual and multiple swimming bodies. Our algorithms rely on remeshed vortex methods enhanced with projection approaches to capture the effects of the fluid on the body, and with a penalization technique, to capture the effects of the body on the fluid [1]. These techniques enable wavelet-based multiresolution discretization [2], effective mapping on supercomputing architectures [3], and provide accuracy, robustness, and flexibility [1]. Simulations in 2D are performed via the Multi-Resolution Adaptive Grid (MRAG) library [2,3]. Simulations in 3D are carried out via our penalization client [1] of the Parallel Particle Mesh library [4]. These flow-structure interaction solvers are embedded in an inverse design cycle that relies on a combination of Evolutionary Optimization Strategies and Reinforcement Learning techniques for the identification of optimal biolocomotion strategies in fluids, in relation to a desired metric or task [5,6,7].

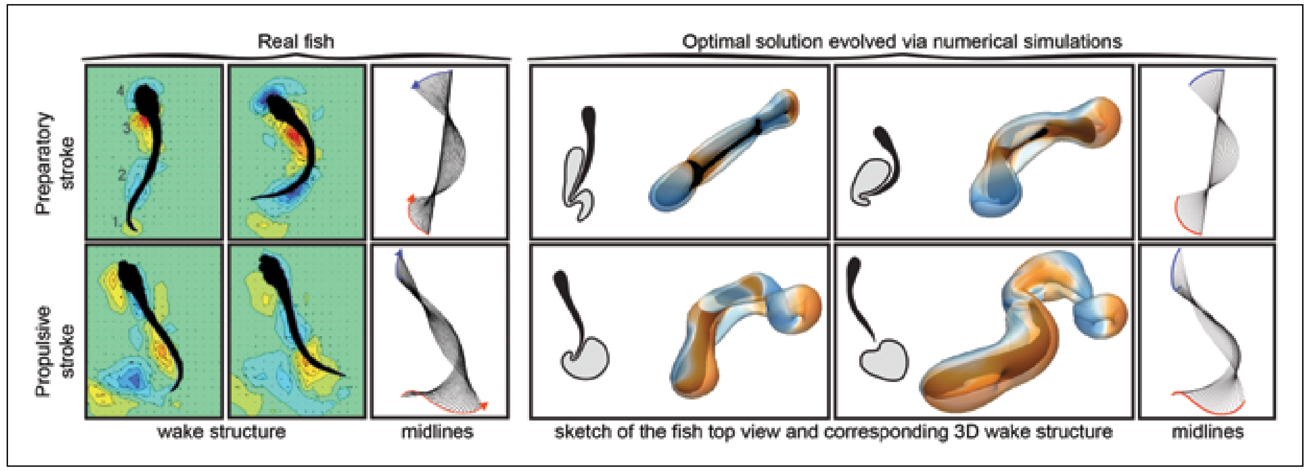

Figure 1: Larval fish developed an optimal escape mechanism: they bend into a "C" shape and then flee from a threat. C-starts' optimality was demonstrated quantitatively by evolving (via evolutionary optimization) fish gaits that maximize escape distances [5]. The identified solution closely resembles real fish escape patterns. Flow analysis reveals the underlying mechanism: fish accommodate a "ball" of water (grey region) in the "C" and then push it with a backflip of the tail to gain momentum in the opposite direction. Therefore, the wake flow structures play a far lesser role than assumed thus far.

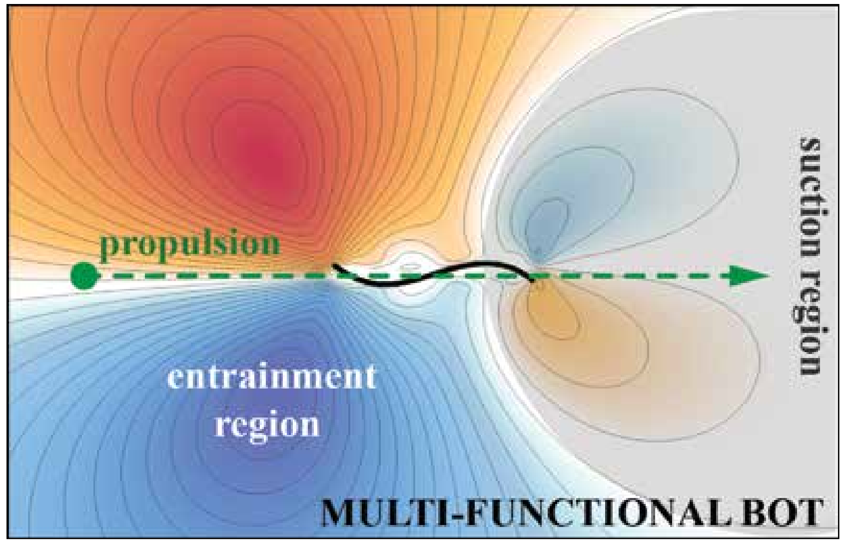

Figure 2: Flexible slender body and wave actuation produce locomotion, suction and entrainment regions.

RESULTS & IMPACT

The coupling of realistic numerical simulations with artificial intelligence techniques is one of the frontiers of Computational Fluid Dynamics and is a unique aspect of this project. We have successfully demonstrated the predictive power of this approach and its ability to provide biophysical insight in the context of rational design of artificial swimmers. For example, we showed that the C-start mechanism (Fig. 1), a widespread escape response among living fish, is optimal as it maximizes the swimmers' ability to channel water displacement into forward acceleration [5]. Furthermore, we showed that artificial swimmers have the potential to outperform biological ones [6]. We are currently focusing on the design of swimmers able to "sculpt" the surrounding flow in order to achieve multi-tasking behavior (Fig. 2).

WHY BLUE WATERS

Our inverse design process entails thousands of flow-structure interaction simulations, each one characterized by billions of computational elements. Without the sheer size and cutting-edge technology of Blue Waters, these investigations simply would not be possible.