Optimum control strategies for maximum thrust production in underwater undulatory swimming

Li Fu*[1], Sardor Israilov[2,3], Jesús Sánchez-Rodríguez , Christophe Brouzet , Guillaume Allibert[4], Christophe Raufaste[5,6], and Médéric Argentina†[5]

[1]Laboratoire de Tribologie et Dynamique des Systèmes – Ecole Centrale de Lyon – France
[2]Institut de Physique de Nice – Université Nice Sophia Antipolis (1965 - 2019), Centre National de la Recherche Scientifique, Université Côte d'Azur – France
[3]Signal, Images et Systèmes – Laboratoire d'Informatique, Signaux, et Systèmes de Sophia Antipolis – France
[4]I3S – CNRS – France
[5]Université Côte d'Azur, CNRS, Institut de Physique de Nice – CNRS INPHYNI UMR7010 – France
[6]Institut universitaire de France – Institut Universitaire de France (IUF), F-75000 Paris, France – France

Abstract

Fishes, cetaceans, and many other aquatic vertebrates undulate their bodies to propel themselves through water. Swimming requires an intricate interplay between sensing the environment, making decisions, controlling internal dynamics, and moving the body in interaction with the external medium. Within this sequence of actions initiating locomotion, biological and physical laws manifest complex and nonlinear effects, which does not prevent natural swimmers to demonstrate efficient movement. This raises two complementary questions: how to model this intricacy and how to abstract it for practical swimming. In the context of robotics, the second question is of paramount importance to build efficient artificial swimmers driven by digital signals and mechanics. In this study, we tackle these two questions by leveraging a biomimetic robotic swimmer as a platform for investigating optimal control strategies for thrust generation.

Our primary objective was to determine the actuation that yields the highest thrust, and thus the highest swimming speed, for underwater swimmers. Considering the complex fluid-structure interaction at relatively high Reynolds numbers, we employed various approaches and methods to shed light on this topic. Notably, reinforcement learning techniques played a crucial role in revealing that the most effective method to achieve high thrust in experiments involves employing a bang-bang controller. This type of actuation oscillates abruptly and periodically between the two extreme command values. To rationalize and validate these experimental results, we studied a simple model using reinforcement learning. The results from this model closely aligned with those obtained through the experimental approach, further reinforcing the effectiveness of the bang-bang controller. Additionally, full 2D numerical simulations of autonomous swimmers confirmed the validity of our findings.

We have successfully illuminated the strategy to attain the highest thrust for underwater

*Speaker
†Corresponding author: mederic.argentina@univ-cotedazur.fr

swimmers, comprising three key messages. Firstly, the command should resemble a periodic square function, exploiting the natural oscillation of the tail-fin system. Secondly, the frequency of actuation needs to be close to that which maximizes tail speed. If damping vanishes, this frequency will approach the body's natural undulation frequency. Lastly, an efficient approach to selecting a nearly optimal swimming gait is to switch the actuation sign as the fin speed becomes too small.