11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

Biological and artificial motility at microscopic scales

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Key Words: *Cell motility, Bio-inspired robotics, Soft robots, Mechanics of active materials.*

The study of locomotion of biological organism and bio-mimetic engineered replicas is receiving considerable and increasing attention in the recent literature. In several cases, such as motility at the micron scale accomplished by unicellular organisms, or the ability to navigate on rough terrains exhibited by insects, worms, snakes, etc., Nature has elaborated strategies that surpass those achievable through current engineering design. The combination of quantitative observations, theoretical and computational modelling, design and optimisation of bio-inspired artefacts is however leading to fast progress both in the understanding of the options Nature has selected and optimized through natural selection, and on the possibility of replicating them (or even improving upon them) in man-made devices.

For example, the swimming strategies of unicellular organisms can be understood, starting from videos of their motion captured with a microscope and processed with machine-learning techniques, by using tools from geometric control theory [1]. In fact, self-propulsion results from non-reciprocal looping in the space of shape parameters, it can be replicated by using actuation strategies that can induce non-reciprocal shape changes, and optimized by solving optimal control problems [2,3].

Crawling motility on solid substrates of several model organisms (snails, earthworms, etc.) can be understood using similar techniques. In the case of crawlers exploiting dry friction, or lubricating fluid layers with complex rheology (such as the mucus secreted by snails), resistance forces are nonlinear functions of the sliding velocity and locomotion is typically accomplished through stick-and-slip. Even when resistance forces are linear in the sliding velocity, if they also depend on the size of the contact region, locomotion is still possible, provided that more elaborate strategies are employed [4]. These are very similar to those that are effective in low Reynolds number swimming, and show that the transition between crawling and swimming motility is much more blurred than what was previously thought. In fact, much can be learned on the physics of micron-scale motility by comparing swimming and crawling motility modes of biological locomotors, and using mathematics to highlight similarities and differences.

A key question is which are the minimal mechanisms needed to make (efficient) self-propulsion possible. In this paper, we will concentrate on the question of how is it possible to extract positional change (i.e., a non-periodic history of positions) from reciprocal shape changes (i.e., a very restrictive class of periodic histories of shape change, obtained by tracing backward and forward a curve in shape space). The famous `scallop theorem' is precisely the statement that this is impossible for low Reynolds number swimming.

We will review recent progress in the theoretical and computational analysis of this issue. In particular, we will analyse swimming and crawling in the presence of `directional' interactions with the environment and study in detail a model of one-dimensional crawlers on a directional surface. By this, we mean a situation in which the resistance force is not odd in the velocity: this may arise for instance on surfaces shaped as ratchets, or when the interaction is mediated by oblique flexible hair (so that by reversing the sign of the velocity to move against the grain, the resistance force does not only change in sign, but may also change in magnitude.)

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