Nanorobot Propulsion in Biological Fluids

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Building, powering, and operating structures that can navigate complex fluidic environments at the sub-mm scale is challenging. We discuss some of the limitations encountered when translating actuation mechanisms and design-concepts from the macro- to the micro-scale. Moving through fluid environments at the scale of micro-organisms for instance presents a different set of challenges compared to those encountered by macroscopic swimmers. Particularly, at low Reynolds number (Re << 1), which indicates a Stokes regime of fluid flow with a dominance of viscous forces over inertial forces, it is known that a simple reciprocating time reversible motion will not result in any net displacement of the swimmer in water. This limitation is known as the "scallop theorem". Hence, asymmetric non-reciprocating actuation mechanisms are required at low Re for many microrobots. Micro-organisms use two non-reciprocal propulsion mechanisms: the travelling wave beats of cilia and the helical rotation of flagella. Mimicking a rotating flagellum requires a rotary motor and power source capable of producing sufficient torque to overcome the high viscous drag at low Reynolds number. One may consider the use of electromagnetic motors, which are ubiquitous in macro-scale robotics. However, electromagnetic motors require sizeable currents which preclude miniaturization. Present designs are limited to the mm-length scales. This is for instance far too large for applications in micro-surgery. Piezoelectric rotary motors do not require large currents and piezoelectric elements can readily be obtained that have small linear dimensions (~250 μm), but they require relatively high input voltages and must therefore always be tethered to a power cable. If the motor is to be powered wirelessly using a battery, then this presents a problem, as thin film lithium ion batteries need large areas ~20 mm^2 for useful power levels. There are therefore no simple compatible combinations of motor and onboard powering source for designing sub-mm micro-swimmers. Hence, we resort to external magnetic fields and the torque they exert on structures that contain a permanent micromagnet or a nanomagnet.

Another major challenge in the field of micro- and nanorobotics is that there are no standard fabrication methods that can be used to build complex 3D structures with functional materials (including magnetic ones) that one needs to realize these structures. Here I will present a recent fabrication advance [1] that we have developed in the lab and that we use to build nanorobots. It has for instance allowed us to realize the smallest synthetic chemical nanomotors [2]. The exciting aspect of this research field is that building and operating such small devices is a highly interdisciplinary task, as the chemistry and biology of the medium is as important as the fabrication and actuation mechanism. It turns out that cork-screw helical structures that mimic bacterial flagella can be well controlled and can be moved through liquids with exquisite control on the micron scale [3]. However, even at 1 to 2 microns such structures are too large to move through the network of biological molecules that one finds in biomedically-relevant media, such as the vitreous humor of the eye or the synovial fluid of the joint. It now becomes necessary to build nanostructures that are so small that they can slip through this network, which is only about a 100nm wide. We have recently built and operated the smallest nanopropellers that have been made to date, and that are able to move through these biomedia [4]. Interestingly, the complexity of the biomedically relevant fluids also presents an engineering opportunity as the particular fluid environment presents an opportunity to realize simple microswimmers – microrobots that cannot move in water because of the "scallop theorem", but that can move in biomedically relevant fluids and tissues [5]. This has opened new possibilities in the design of micro- and nanorobotic systems that are designed with biomedical applications in mind.

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[3] “Nano-Propellers and their Actuation in Complex Viscoelastic Media”, D. Schamel, A.G. Mark, J.G. Gibb, C. Miksch, K.I. Morozov, A.M. Leshansky, P. Fischer, *ACS Nano* **8**, 8794 (2014).

[4] Swimming by Reciprocal Motion at Low Reynolds Number", T. Qiu, T.-C. Lee, A. G. Mark, K. I. Morozov, R. Münster, O. Mierka, S. Turek, A. M. Leshansky, P. Fischer, *Nature Comm*. **5** 5119 (2014).