Bioinspired Design and Energetic Feasibility of an Autonomous Swimming Microrobot

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Abstract. A mobile microrobot is an untethered robotic device with typical size ranging from few micrometres to few millimetres. Endowing such a microrobot with autonomy-oriented capabilities, e.g. self-propulsion and self-powering, represents a scientific and technological challenge that requires innovative approaches. Bioinspiration provides fundamental cues for designing microrobots, enabling the development of working devices. Here we present the conceptual design of an autonomous swimming microrobot relying on biomimetic glucose-based powering, reporting a preliminary analysis on its energetic feasibility.

Keywords: swimming microrobot, bioinspiration, power, glucose, fuel cells.

1 Introduction

Mobile swimming microrobots are untethered devices with typical size ranging from few micrometres to few millimetres and able to move in liquids. Recently, they have drawn increasing attention due to their envisioned applications in medicine and to basic scientific and technological interests [1-2]. Current mobile microrobots either rely on wireless actuation by external purposely-provided sources of energy, e.g. magnetic fields [3], or consist of swimming microorganisms, possibly controlled by external fields, adopted as such, modified or attached to artificial microstructures [4].

Endowing an artificial swimming microrobot with autonomy-oriented capabilities, such as self-propulsion and self-powering, could be the first step toward a new generation of advanced microrobots [5]. In addition, dealing with this challenge could drive the demand for technological solutions at the microscale.

2 Conceptual Design

Two critical aspects in the design of artificial autonomous swimming microrobots are self-propulsion (propulsion by internal actions) and self-powering (internal generation of power), since adopting traditional components is not possible at these scales. Therefore, innovative design approaches are needed. Among them, bioinspiration provides essential design cues that enable the development of working devices [1].

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The issue of self-propulsion involves two different problems, namely: adopting propulsive body deformations; achieving these through embedded actuators. In previous works [6-7] we addressed the former by defining a propulsion mechanism inspired by metachronal waves in ciliates. This is based on a small-amplitude, longitudinally-travelling sinusoidal perpendicular deformation of an active surface enveloping the microrobot. The envisioned microrobot has a cylindrical shape with hemispherical front and rear (Fig. 1). In addition, we preliminary addressed the design of the active surface, emphasizing the limitations of current microscale actuation technologies. Since their suitability for autonomous microrobots is strictly constrained by power aspects, the estimation of the available power is crucial in microrobots design.

Microorganisms, as living beings, draw energy from their environment. This allows them to carry none or very limited energy on-board. Scavenging some form of energy from the surroundings could be an interesting approach for self-powered microrobots, as well [2]. A number of devices scavenging different forms of energy, e.g. chemical, thermal or mechanical, have been developed at the milli/microscale [8].

Considering their envisioned applications involving navigation in bodily fluids, the environment of swimming microrobots will be rich in chemicals to be exploited for generating power, such as the ubiquitous glucose. On the contrary, natural thermal gradients will be almost absent due to homeostasis. In addition, vibrations and other sources of mechanical power are not suitable to this particular mobile embodiment. Therefore, autonomous swimming microrobots powered by scavengers of chemical energy, such as fuel cells relying on the oxidation of glucose, can be envisioned [2].

3 Estimation of Available Power

Glucose Fuel Cells (GFCs) are 2D devices that generate electrical power by oxidising the glucose dissolved in the fluid they are in contact with. They rely either on noble-metals catalyst (non-enzymatic GFCs) [8] or on biocatalysts (enzymatic GFCs) [9]. In physiological conditions, enzymatic GFCs have higher power outputs (>100 $\mu W/cm^2$) but lower duration (days) than non-enzymatic ones (<10 $\mu W/cm^2$, months), which can also be microfabricated with standard lithographic techniques [8].

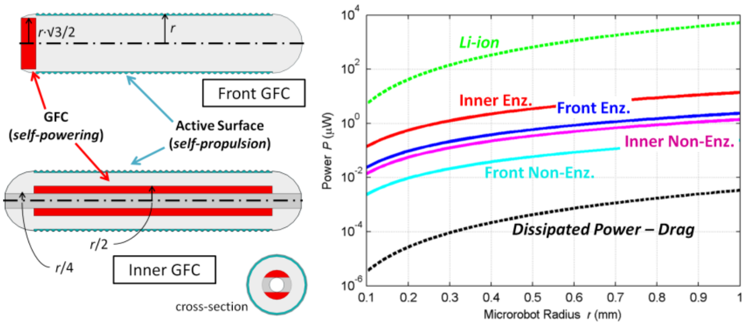

Fig. 1. Estimated available power for different microrobot designs: the two configurations of the microrobot (left); power from different GFC configurations (right): as reference we report the power from a hypothetic microscale Lithium-ion battery and the power dissipated by drag

Since in the proposed design the lateral surface of the microrobot is dedicated to propulsion, two viable ways for having the GFC in contact with the fluid are either to place a GFC on the front and rear surfaces or within an inner channel, with the fluid passing through the microrobot). Here we analytically estimated the available power from a GFC-based power supply considering two different designs of the microrobot, one with a front GFC (simpler but with smaller active surface) and one with a GFC placed in an inner channel (more complex but with larger active surface – see Fig. 1). For each design we considered both the enzymatic and non-enzymatic case (assumed output surface power densities $p_{\text{Enz-GFC}}$ = 100 μW/cm^2 and $p_{\text{NEnz-GFC}}$ = 10 μW/cm^2). We considered the radius r of the microrobot varying in the range 0.1 – 1 mm, with the other dimensions varying accordingly (total length $l_{\text{TOT}} = 10r$, length of the active surface for propulsion $l_{\text{ACT}} = 8r$). This resulted in the area of the GFC electrodes A_{GFC} of both configurations varying, as well. The results reported in Fig. 1 show that even the worst configuration (front non-enzymatic GFC) would supply an amount of power ($P_{\text{supply}} = p_{\text{GFC}} \cdot A_{\text{GFC}}$) much larger than that dissipated by dragging the microrobot in the fluid at a reference relative speed of 1 bodylength/s ($P_{\text{drag}} = C_d \cdot \eta \cdot r \cdot v^2$). In addition, the results show that the available power could be further increased by adopting more advanced solutions, such as enzymatic catalysts and/or an inner channel design. Hence, this analysis returns fundamental power constraints for the design of the actuation elements for self-propelled and self-powered artificial swimming microrobots.

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