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Controlled Nucleation and Release of Microbubbles for Novel Buoyancy Mechanisms in Miniature Robotic Swimmers

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Microbubbles are often byproducts of chemical processes or entities existing on submerged surfaces in liquid environments. Bubbles may hinder the operation of devices or the balance of chemical reactions and are often regarded as a problem. However, they may also be used for separation processes, in which hydrophobic particles are separated from aqueous media and in lubrication underwater, namely reducing friction between liquids and solid surfaces.

Interestingly, there are several examples in nature in which bubbles are used for regulating buoyancy underwater. One example is the purple snail (Janthina janthina), which stabilizes bubbles in order to float at the water-air interface of the ocean. There, it finds nutrition and is able to reproduce. Therefore, stable bubbles are important for its existence. Another example is the backswimmer (Notonectidae, Anisops). This is an aquatic insect, capable of regulating its buoyancy underwater by using surface anchored bubbles. When it enters the water, it entraps an air bubble in a superhydrophobic hairy structure covering its abdomen. This bubble creates a stable plastron. Namely, a layer of external gas supply which can flow both to and from the water. While this bubble is mainly used for respiration, it also functions as an external inflatable gas reservoir for buoyancy regulation. Hemoglobin in the Backswimmer body is used to store and release oxygen to the entrapped bubble, reversibly. This way, it can reach neutral buoyancy without further energy consumption.

The ability to control the nucleation of bubbles opens many possibilities to mimic buoyancy regulation in nature and apply it in robotic systems. The animals using bubbles to regulate buoyancy in nature are relatively small, cm to mm scales. Therefore, mimicking their operation may promote the miniaturization of robotic swimmers which usually rely on inflatable tanks such as the ones used in submarines. There, also energy consumption is a central aspect, as working against hydrostatic pressure may be highly energy consuming. On the contrary, nucleating gas bubbles can be achieved through the splitting of water into oxygen and hydrogen on catalytic surfaces, using low voltages. The advantage of such a mechanism is the use of the surrounding water to “fuel” the bubbles’ growth.

Yet, in order to regulate buoyancy, one has to find a way to control the release of surface anchored bubbles. This includes electro-wetting, catalytic reactions and mechanical vibrations. The latter is especially attractive as it allows finer control over bubble detachment, depending on the oscillations’ amplitude and frequency.

In this study, we develop a small, centimeter-scale, backswimmer-inspired untethered robot (BackBot) with auto-buoyancy regulation through controlled nucleation and release of microbubbles. The bubbles nucleate and grow directly on onboard electrodes through electrolysis, regulated by low voltage. A bubble-entrapping 3D-printed canopy is introduced to create a stable external gas reservoir. To reduce buoyancy forces, the bubbles are released through linear mechanical vibrations of the canopy, decoupled from the robot's body. Through pressure sensing and a proportional integral derivative control loop mechanism, the robot auto-regulates its buoyancy to reach neutral floatation underwater within seconds. This mechanism can promote the replacement of traditional, and physically larger, buoyancy regulation systems such as pistons and pressurized tanks, and enables the miniaturization of autonomous underwater vehicles.