Backswimmer-Inspired Miniature 3D-Printed Robot with Buoyancy Autoregulation through Controlled Nucleation and Release of Microbubbles

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1. Introduction

In nature, one can find a variety of materials and mechanical systems that are evolutionarily optimized for underwater locomotion and for the regulation of buoyancy. Most well known are fish, sharks, and other aquatic species relying on gas-filled swim bladders and fine tuning of the chemical composition in internal organs, respectively. However, a surprising mechanism for regulating buoyancy is demonstrated by the aquatic insect Notonectidae, Anisops, commonly known as the backswimmer. By regulating the amount of oxygen bound to hemoglobin in its body, the backswimmer alters the volume of an external gas bubble, trapped in a superhydrophobic hairy structure on its abdomen (Figure 1a). The bubble is stabilized by the superhydrophobic hairs (setae) and is primarily used for respiration. Therefore, it was a surprising finding that this bubble is also used to regulate buoyancy and even allows the backswimmer to reach neutral buoyancy underwater for prolonged periods. Insects are usually negatively buoyant, meaning that their density is slightly higher than water. Therefore, it is possible for them to reverse the buoyancy forces underwater by small variations in the volume of the air plastron attached to their body.

Locomotion using bubbles in synthetic systems has been previously demonstrated from nano- to macroscales. Many of these studies used bubble nucleation through catalysis. For example, the splitting of H₂O₂ on metals or alloys is convenient for propelling small colloids and particles. Urea and glucose have been demonstrated as biofuels, and enzymes as catalysts, to propel particles in a more environmentally friendly manner. To eliminate the dependence on fuel, which may pollute and eventually deplete, other mechanisms to induce bubble nucleation are of interest. For this, electrolysis is an attractive choice, relying on the splitting of water into oxygen and hydrogen in the form of bubbles. While many of these studies focused on particle propulsion due to bubble generation, there are only few examples for production of bubbles for regulating buoyancy. Bubble attachment to particles, however, is broadly used to induce flotation in separation processes. Bubbles can generate a broad range of buoyancy forces, depending on their size, down to nN scale for submillimeter bubbles. Therefore, they withhold great potential to promote the miniaturization of robotic devices, offering fine tuning of buoyancy.

Bubbles’ adhesion to surfaces increases with the hydrophobicity of the surface, density of surface cavities and defects, roughness, and local decrease in pressure. On the contrary, detaching gas bubbles from submerged surfaces can be achieved by electrowetting and mechanical forces, and when buoyancy forces overcome pinning forces. In addition, when
bubbles go through rapid inertial growth, they may detach early from the surface.\[28\] Otherwise, surface-anchored bubbles in steady state underwater change volume over time due to diffusion of gas into and from the bulk water.\[29\] This, for example, limits the time some insects and other arthropods spend underwater, relying on an air plastron for breathing.\[30\]

As insects are generally small, up to few centimeters, and light, with up to few grams in weight, they are subjected to interfacial forces, especially at the water–air–solid interface.\[31–35\] While these forces can be deadly for small insects, for example, when flying insects get trapped at the water–air interface, many of them adapted to interfacial forces in terms of materials, design, and modes of locomotion.\[35–38\] Such adaptations in nature can provide guiding lines for the development of miniature robots.\[39\]

In this study, we design, fabricate, and develop a small, centimeter-scale, robot that can autoregulate its buoyancy and achieve neutral floatation underwater (Figure 1b). Bubble nucleation and growth are driven by the splitting of water into oxygen and hydrogen on onboard electrodes (Figure 1c). The bubbles are entrapped and stabilized on a 3D cellular structure at the top of the robot. The release of bubbles is achieved by mechanical vibrations (Figure 1d). An ad hoc device is designed to decouple the mechanical vibrations from the robot’s body, to eliminate its possible destabilization and rollover during bubble release. Overall, the BackBot is capable of self-regulating its buoyancy underwater, by controlled nucleation, growth, and detachment of gas bubbles. This principle can be used to miniaturize autonomous underwater vehicles with self-regulation of buoyancy and develop small swimmers used to study cooperative motion underwater.\[40\]

2. Results and Discussion

2.1. Robot Design

The BackBot compartments are depicted in Figure 2. It is constructed of a main 3D-printed hollow chamber (main body), with an onboard electrode at the top and a 3D-printed cellular canopy on top of the electrode (Figure 2a).

A brass plate with 26 threaded holes was positioned at the bottom outer part of the robot hull (see also Figure S1, Supporting Information). The buoyancy device was designed to be easily dismounted from the robot. The bottom weight allows stabilizing the robot by lowering the center of gravity underneath the center of volume. Fine adjustments are made to reach a desired density by adding or removing setscrews from the brass plate, namely, “trimming.” In addition, we use the set of weights to align the robot and enable stable spatial orientation in bulk water (Figure 2b). The overall weight of the robot is 112 g and it is mostly made of 3D-printed polymeric parts. Its average density, $\rho_{\text{robot}} = 1.0025 \, \text{g cm}^{-3}$, was designed to be slightly larger than the density of the surrounding water in order for the robot to be negatively buoyant in its nonactive state. Figure 2c shows the principle of operation of the BackBot and the buoyancy autoregulation. Initially, the BackBot is situated at the bottom of a water tank. Upon applying voltage, bubbles nucleate on the electrodes. Some bubbles remain anchored to the electrode, while some leave the surface and float until they reach the canopy. There, they become entrapped and are stabilized at the solid–water interface. Consequently, the BackBot becomes positively buoyant and starts ascending. To balance the positive buoyancy forces, the linear oscillation mechanism operates, detaching bubbles from the canopy surface. This step is iterative and eventually leads to neutral buoyancy.

2.1.1. Microbubbles’ Nucleation, Growth, and Entrapment through Electrolysis

The buoyancy autoregulation device is depicted in Figure 3. At the top of the device, a 3D-printed canopy, made of a curved lattice structure, is used to entrap bubbles. A crank arm, mounted on a DC motor shaft, converts the rotational movement generated by the motor to linear movement of the canopy.
Two electrodes, made of a 0.2 mm-thick stainless steel in a comb configuration, produce gas bubbles through electrolysis under voltage. A cross section of the canopy reveals the lattice structure used for capturing bubbles (Figure 3ai). Each lattice unit cell is shaped as an extruded ring sector, which follows the canopy curvature. The extruded dimensions correspond to 2.5 mm, sector angle of 6°, and thickness of 2.5 mm.

3D printing enables a simple way to adjust the bubble-entrapment unit. Three different unit cells were designed and tested to achieve optimal capturing of the gas bubbles as they pass through the lattice voids. Hybrid body-centered cubic (BCC) and face-centered cubic (FCC) unit cells of 2.5 mm edge length showed good capturing ability of the gas bubbles (Figure S2, S3, Supporting Information). Specifically, only a fraction of microbubbles managed to pass through the bars without being trapped.

A top view of the buoyancy device showing the crank arm, DC motor, and electrodes is depicted in Figure 3aii). The electrodes comprise two interlocking combs with 0.5 mm spacing between their scales. This geometry maximizes the surface area for bubble nucleation and increases the electrostatic fields between the combs. This configuration yields small gas bubbles of up to 1 mm in diameter. Such bubbles detach spontaneously from the electrodes and float upward to the canopy. The importance of bubble detachment from the electrodes lies in the difficulty to release them from this surface in a controlled fashion. A cross section of the assembled configuration of the buoyancy regulation device is depicted in Figure 3aiii). While the canopy is designed to linearly vibrate and regulate bubble release, the electrodes cannot be freed from anchored bubbles. This results in two counterproductive outcomes. First, anchored bubbles reduce the electrolysis efficiency and consequently, the ability to generate maximal buoyancy forces. Second, anchored bubbles alter the density balance of the device and may interfere with the control loop mechanism regulating the buoyancy, as will be discussed in the next parts. Figure 3b shows a representative curve of the total force acting on the BackBot, depending on the duration of applied voltage. The overall force increases linearly with time, in a rate of 0.031 mN s⁻¹ (Figure S4, Supporting Information). Figure 3c illustrates the operation of the device. Microbubbles nucleate and grow on the surface of the electrodes, detach and float upward, and become entrapped in the canopy is situated on top of the electrode.

The mechanism is designed to function around room temperature. Changing the water temperature may result in several parallel outcomes. Namely, surface tension and viscosity of water decrease with temperature and are expected to facilitate nucleation. However, the solubilities of oxygen and hydrogen in water decrease with temperature and, therefore, may alter the gas exchange rates between the bubbles and their surroundings. These parallel mechanisms may require adjusting the hydrolysis parameters.

2.1.2. Bubble Release through Linear Vibrations

The bubble controlled release mechanism is based on linear oscillations of the canopy (Figure 4). The gas bubbles, anchored to the canopy, are subjected to lateral forces resulting from oscillations at a frequency of 10 Hz over a span of 6 mm (Figure 4a, inset). This frequency is high enough to induce detachment of bubbles, but small enough to be compatible with the available battery power. The power consumption of the motor corresponds to 1.875 W. This controlled release mechanism decouples the oscillations of the canopy from the main body of the BackBot and inhibits...
destabilization of the device. Figure 4b depicts the conversion mechanism from rotation to linear motion. A crank arm is fitted on a DC motor shaft, and a pin on the crank arm is allowed to move inside an embedded slot in the canopy part. This pin-slot configuration converts the rotational motion of the motor shaft to linear motion of the canopy (Figure 4c). As the canopy oscillates around the center position, gas bubbles detach from the structure and release to the bulk water.

The capillary length of water in air is given by

\[ l_c = \sqrt{\frac{\gamma}{\rho g}} \]

with \( \gamma \) is the water–air interfacial tension, \( \rho \) is the water density, and \( g \) is gravitational acceleration. For water droplets in air, this corresponds to roughly 2.7 mm. We expect that the capillary length calculated for gas bubbles underwater will be similar. Meaning, bubbles below this size will remain attached to the canopy, while larger bubbles will detach spontaneously due to buoyancy forces overcoming the capillary adhesion forces. Indeed, microbubbles, up to 2 mm in diameter, show significant pinning on the lower bars of the canopy.

The lateral adhesion of a bubble to a surface is given by Equation (1).

\[ F_{\text{Lateral}} = \gamma L_s (\cos \theta_{\text{Rec}} - \cos \theta_{\text{Adv}}) \]  

(1)

\( F_{\text{Lateral}} \) is the lateral adhesion force, acting at the contact of a bubble with a solid surface, \( \gamma \) is the surface tension of the liquid, \( L_s \) is the contact width, and \( \theta_{\text{Rec}} \) and \( \theta_{\text{Adv}} \) are the receding and advancing contact angles, respectively. In this case, the contact angles correspond to \( \theta_{\text{Adv}} = 113 \pm 6^\circ \) and \( \theta_{\text{Rec}} = 71 \pm 12^\circ \). This results in adhesion forces from approximately few \( \mu \)N to few dozen \( \mu \)N for bubbles ranging between 100 \( \mu \)m and 1 mm in diameter, respectively. While the adhesion forces scale linearly with the bubble radius, the mechanical forces, due to oscillations, scale with the bubble volume. Therefore, the estimated forces acting on the surface-anchored bubbles due to the mechanical oscillations correspond to roughly \( \approx 10^{-3} \mu \text{N} \) for bubbles with 100 \( \mu \)m diameter but up to \( \mu \)N scale for bubbles 1 mm in diameter. For bubbles larger than 1 mm in diameter, buoyancy forces become more dominant. In practice, this means that bubbles of up to few hundred micrometers in diameter cannot be mechanically released from the canopy, while bubbles of roughly 1 mm in diameter and above can. This agrees very well with the description of phase I and phase II (Figure 4d). In phase I, larger
bubbles detach, causing quick reduction of buoyancy forces, followed by phase II, in which smaller bubbles remain attached to the canopy, resulting in only small residual decrease in the buoyancy force. In case the robot operates in flowing water, bubbles may release from the canopy in an undesired way, leading to a destabilization. A closed control loop will be later implemented in the robot to compensate for such variations in the force balance, as will be discussed in Section 2.1.3.

The electrolysis power consumption corresponds to 0.75 W. In the ascending phase, energy consumption from the initial bubble production until floatation corresponds to roughly 23 J. Further changes in depth correspond to energy consumption of 18 J, on average, per transition between ascending and descending, within a range of ≈30 cm tested in this study. Overall, the BackBot ascends and descends while consuming power in the within a range of

\[ \text{energy consumption} \approx 23 \text{ J} \]

Consequently, characteristic times for generating positive buoyancy forces correspond to a few dozen seconds and transitioning from positive to negative buoyancy to few seconds. In practice, during the first cycle of bubble generation, the canopy becomes saturated with bubbles and the force working range reduces. As a result, the timescale for transitioning between positive and negative buoyancy states reduces to few seconds (Figure S4, Supporting Information).

2.1.3. Buoyancy Autoregulation

Finally, we introduce a closed control loop using a pressure sensor and a proportional integral derivative (PID) controller (Figure 5).

The main electronic components include a custom-made printed circuit board (PCB) with the necessary electronic components such as the voltage regulator, H-bridge-integrated circuits (ICs), resistors, and miniature electrical connectors (Figure 5a). A wireless communication module allows communication between the BackBot and a remote station. An external voltage supply port allows bypassing the battery when long experimentation time is needed. Figure 5b shows an exploded view diagram of the pressure sensor, the front cap, and the two securing screws and rubber O-rings for sealing the system. Figure 5c shows a sketch of the automation process governing the buoyancy regulation. The closed-loop control algorithm, operating at a rate of 10 Hz, receives an input parameter from the operator (desired depth) and depth measurement from the pressure sensor (actual depth). The difference between the two parameters is the “depth error,” fed into PID control algorithm. The output of the algorithm is a value ranging between −255 and +255, corresponding to the electrical signal intensity. This is sent to the electrodes and motor driver to produce or release bubbles from the buoyancy device, accordingly. As a result, changes in depth are achieved by physical movement of the robot along the z-axis (see also Figure S5, Supporting Information).

We then characterize the BackBot ascending and descending rates over time (Figure 6). The zero position corresponds to the water–air interface. Ascending rates correspond to 11.3 ± 2.7 mm s⁻¹ (Figure 6a). This rate depends on the duration of applied voltage and is tunable. In the opposite direction, when the BackBot descends, rates correspond to 31.5 ± 22.4 mm s⁻¹ (Figure 6b). Variations in the descending rate are the results of residual entrapped gas bubbles in different locations of the robot, including the canopy, main hull and external areas, and could not be entirely avoided. Figure 6c shows controlled ascending and descending of the BackBot until it reaches neutral floatation, in an autonomous way, through the control PID loop. The vertical range for autocorrection of the BackBot position is roughly 2 cm. It can remain stable in a fixed vertical position, limited by the diffusion rates of the gas from the surface-anchored microbubbles into the bulk water and up to few hours. [49]
Figure 7 shows a variety of motion patterns in the vertical direction, generated by manual control (Figure 7a,b, see also Video S2, Supporting Information) and autonomous control (Figure 7c,d). In the manual mode, the operator chooses two control signals: one for the electrodes and one for the motor generating the mechanical vibrations. These are sent from the remote station to the robot wirelessly. Average ascending and descending velocities correspond to 17.7 ± 0.7 and 23.5 ± 2.5 mm s⁻¹ for the first \((t_1 + t_2)\) and second \((t_3 + t_4)\) cycles, respectively (Figure 7a). In Figure 7b, the potentiometer controlling the electrodes (POT-E) and the DC motor (POT-M) was controlled more precisely, leading to a more moderate movement of the robot. A first ascend \((t_1)\) started at a depth of 150 mm up to a depth of 75 mm, at an average velocity of 6.8 mm s⁻¹. Then, the BackBot stabilized \((t_2)\). A rapid movement of the canopy made the robot sink at an average velocity of 48 mm s⁻¹ \((t_3)\) until it reached the bottom of the water tank \((t_4)\). Bubble production was renewed, and the robot ascended to a depth of 75 mm at an average velocity of 14.5 mm s⁻¹ \((t_5)\) for 4 s \((t_6)\). Finally, the BackBot climbed to a depth of 49 mm and maintained its position at this depth \((t > t_6)\).

In the automated mode, using the closed-loop PID control algorithm, a target depth was chosen by the operator and sent to the BackBot (Video S1, Supporting Information). We tune the gain factors of each term in the PID control algorithm: proportional term gain, \(K_p\), integral term gain, \(K_i\), and derivative term gain, \(K_d\), to improve the motion control in terms of overshoot and time until the target depth is reached. At first, values of \(K_p = 10\), \(K_i = 0\), and \(K_d = 0\) were used. This resulted in an overshoot of 35 mm, reaching the target depth (within 5% error) after 30 s (Figure 7c). Additional tuning of the proportional and integral parameters improved the performance. Introducing the derivative parameter, \(K_d\), minimized the overshoot and lowered the setting time. The values were now set to \(K_p = 2.5\), \(K_i = 0.9\), and \(K_d = 0.1\) (Figure 7d). Consequently, the rise time reduced to 9.1 s, with no overshoot. The setting time required for the BackBot to reach the target depth, within an error of 5%, reduced to 15 s. Furthermore, after the target depth was reached, a new target depth was sent to the robot to test how the system responds to changes. After hovering at the first target depth (Figure 7d, horizontal dashed red line) for 25 s, the robot ascended to the new target depth (horizontal purple dashed line). The intermediate green dashed line indicates a disturbance that the buoyancy device was able to overcome when small bubbles managed to escape the canopy \((t = 43–46.75\) s). The controller was able to compensate for the loss and reach its target depth.

As long as the robot is connected to an external power supply through cables, the experiment time has no limitation. If the battery is used, the characteristic duration of operation depends on the activities of the robots, namely, how often it needs to change vertical position and therefore use bubble nucleation or mechanical vibrations for their release. In the frame of this study, the robot could operate for roughly half an hour, relying on the battery only (Video S3, Supporting Information). When the vertical position is maintained and no nucleation or release are further needed, the battery could operate for longer durations of more than an hour.

3. Conclusion and Outlook

In this work, we presented an automated mechanism for controlling the buoyancy of an untethered underwater vehicle. This mechanism does not rely on inflation and deflation of an air tank, does not involve the use of pistons, but rather controlled generation and release of surface-anchored bubbles. A closed-loop
control algorithm induces self-regulation of buoyancy, reduces inaccuracies in positioning, and the time to reach a target depth down to a few seconds, considering a depth difference of few dozen centimeters. Due to reduced energy consumption, the robot can operate up to approximately half an hour, relying on a battery.

In outlook of this work, this mechanism will be integrated in an underwater robotic swimmer that will be able to propel and propagate underwater. In a broader perspective, this platform will be used for developing a group of self-propelled underwater swimmers and for investigating the interactions between them, including fulfilling mutual tasks, collaboration, and reciprocal processes.

4. Experimental Section

3D Printing: The robot frame and buoyancy device components were fabricated using additive manufacturing technology (MJP-2500 plus, 3D Systems, voxel size of ≈25 μm) using Visijet M2R-CL photopolymer. All parts were postprocessed in accordance with the manufacturer guidelines and included immersing the parts in mineral oil bath and soapy water at 60 °C. All parts were coated with silicone grease (Dow Corning high vacuum silicone grease) to ensure good sealing. The printed material was intended to perform in room temperature. According to the manufacturer, the heat distortion temperature at a load of 1.82 MPa corresponded to 43 °C. However, small plastic deformations start already at lower temperatures. This may interfere with the sealing of the robot and result in leakage.

Prototype Fabrication and Assembly: The 3D models were designed and evaluated using Solidworks CAD software. CNC Laser cutting technology (Fiber Laser) was used to cut the electrodes (stainless steel 304, Scope Metal Group Ltd.). The electrodes were glued with double-sided adhesive or instant glue. The laser cutter was also used to cut sheets of poly-(methyl methacrylate) (PMMA) for various experimental setup jigs. CNC milling was used to manufacture metal parts with complex geometry. PCB manufacturing was used to produce the custom-made electrical circuit board needed for the project (JLCPCB Ltd.).

Hardware and Electrical Components: Two cells, 7.4 V, 200 mAh, rechargeable Lipo battery, provided the necessary energy for the robot.

Figure 6. Buoyancy regulation of the BackBot during a) ascending, b) descending, and c) reaching neutral floatation.
The wireless communication module established full-duplex communication channel with the microcontroller via UART protocol and was paired with another module located on the PC side via Bluetooth protocol. The depth reading was done with a pressure sensor (TE MS5803-14BA) mounted on the robot body and was interfaced directly with the surrounding water. The pressure sensor established a full-duplex communication channel with the microcontroller via I2C protocol. Arduino Nano 33 BLE Sense Microcontroller was used. Power consumption when only controller and communication modules operate corresponded to 0.26 W.

**Figure 7.** BackBot manual and automated operation. Depth profiles include a) rapid ascending and descending and b) ascending and descending with delay time in between. c) Depth profiles of automated buoyancy regulation with overshooting and d) reaching a target depth precisely. Reducing overshoot is achieved by tuning the PID closed loop.

The measurements were performed at specific time intervals, depending on the time scale of interest.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
3D printing, buoyancy regulation, controlled nucleation of bubbles, electrolysis, robotic swimmers

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