Submersible Soft-Robotic Platform for Noise-Free Hovering Utilizing Liquid–Vapor Phase Transition

Jie Han, Weitao Jiang,* Hongjian Zhang, Biao Lei, Lanlan Wang, and Hongzhong Liu

Hovering at any depth, is one of the most important requirements for underwater robotics, which calls for large-range buoyancy control ability. Although various underwater robotics have been proposed and developed, the requirements of noise-free, environmental tolerance, and low energy consumption in hovering manipulation, are still attracting a lot of attention for underwater tasks. Herein, a submersible soft-robotic platform driven by the self-contained liquid–vapor phase transition is developed. The proposed soft-robotic platform precisely modulates its buoyancy, showing an excellent positioning ability underwater. The proposed soft-robotic platform performs reversible rise-and-sink motions underwater, and generate a buoyancy force of 0.93 N (131% of its weight) with an accuracy of ±2.5 mN, at a heating temperature of 63 °C. It shows that more than 40% of the total buoyancy change is achieved within 55 s, and the platform hovers in any depth in a range of 450 mm (limited by the adopted water container) in 18 s, with positioning fluctuation of 17.42 mm. This soft-robotic platform demonstrates active vertical motions in water and suggests a feasible approach to develop noisy-free and high-reliability underwater robots, which guide the further design of autonomous underwater vehicles (AUVs).

Along with the continuous development in ocean exploration, there is a growing interest in the underwater robotics and submersible vehicles for aquatic environment surveys, biological observation, and oil spill examinations.[5–3] We drew inspiration from nature to design underwater robotics. The said robots mimic the movements and appearance of sea animals, leading them to not only blend in the environment but also this allows us to approach the animals to close proximity without disturbing their ecosystem or posing a threat on them.[4] However, excellent mobility is not enough for underwater robotics to truly explore 3D space in water at different depths (hovering), which calls for compact, lightweight, and non-noisy buoyancy control devices.[5–7]

To achieve effective hovering under the sea, various buoyancy control mechanisms have been proposed in the past for underwater robotics. Conventional underwater robotics, driven by mechanical components such as electric motors and electromagnetic actuators, usually control buoyancy by flooding/drainage of water and have limitations in terms of high noise, bulky system, volume, and nonreusable and sophisticated control.[8,9] Submersible soft robotics inspired by marine creatures with excellent buoyancy control performance have attracted growing attention in the past 10 years, and soft robots with novel bionic buoyancy control schemes and moving strategies have been proposed.[3,5,10,11] Yoshii and coworkers controlled the buoyancy of the underwater robot, utilizing the solid–liquid phase-transition-induced volume change by heating paraffin wax[12] and achieved less than 17% in volume change. Li and coworkers and Zhu and coworkers used artificial swim bladders made of dielectric elastomer to achieve the buoyancy variation of less than 0.5 N,[13,14] which needs a high voltage of 10 kV and bulky equipment. Similarly, Chen and coworkers controlled the volume of an artificial swim bladder by creating bubbles via electrolysis,[15] as the system is scaled up in size, the realizable change in volume becomes insufficient. Rus et al. proposed a scheme to control the buoyancy unit by combining a small compressed CO2 tank with a soft artificial bladder.[7] Despite its small size and low power consumption, it is irreversible and requires periodic replacement of gas cylinders. New methods for buoyancy control still deserve to be explored, to meet the requirements of a wide range of reversible buoyancy adjustment capabilities, simple and

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compact design, light weight, biofriendly, rapid response, effortless control, and silent operation.

The buoyancy control capabilities that marine organisms have mastered through hundreds of years of evolution inspired us a lot, such as the sperm whales which achieve neutral buoyancy at different depths by controlling the temperature of the spermaceti oil in its head\cite{16} and the deep-sea sharks which regulate the oil content of their livers to balance the weight in seawater of their other tissues precisely.\cite{17} The realization of a wide range of reversible buoyancy control capabilities through temperature changes has become a very competitive mechanism for submersible devices. Recently, Jiang and coworkers proposed a soft actuator that can generate large reversible deformation based on liquid–vapor phase transition,\cite{18} which holds the advantages of the self-contained working fluid, considerable reversible volume change ability, high accuracy and repeatability, as well as excellent response linearity control.\cite{19} Given the advantages of the liquid–vapor phase transition process, we applied this mechanism to the advanced submersible soft-robotic platform to achieve noise-free and large-scale buoyancy control ability that can hover underwater. Although the solid–liquid phase change process of paraffin wax has been used for buoyancy control for a long time, research has been conducted on applying the liquid–vapor phase transition mechanism to the large-scale buoyancy control of underwater robotics. In this work, we have developed a bioinspired submersible soft-robotic platform utilizing liquid–vapor phase transition, which is capable of generating a buoyancy force of 0.93 N (131% of its weight) at a heating temperature of 63°C (with an initial temperature of 30°C), achieving more than 40% of the total buoyancy change rapidly within 55 s while floating up more than 450 mm (18 times of its length) in 18 s. This submersible soft-robotic platform could address the current limitations of submersible systems and pave the way for next-generation underwater soft robotics.

As shown in Figure 1a, the driving mechanism of the proposed submersible soft-robotic platform relies on the liquid–vapor phase transition of the capsuled liquids, as well as the volume change in the superelastic soft robotic body induced by the increase in internal pressure. To demonstrate the driving principle of the proposed submersible soft-robotic platform, a bioinspired prototype is designed and prepared, as shown in Figure S3, Supporting Information. The adopted liquid

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Figure 1. Schemes of the liquid–vapor phase transition mechanism and its application to the bionic submersible soft-robotic platform. a) The low-boiling-point liquid will undergo a reversible transition from the liquid phase to the gas phase when heated and cause the superelastic outer wall of the soft-robotic platform to expand. This expansion will cause a change in the volume and directly change the buoyancy force of the system, thereby driving the soft-robotic platform to float or hold vertical positions in the water. The inset shows the simulation results of the expansion and volume increase of the superelastic soft-robotic platform when the internal pressure of the soft robotic increases during the heating process. b) The volume change of the liquid storage cavity of the soft-robotic platform under the effect of pressure difference between internal and external pressure was conducted by FEA, and the results show that the volume increment can be more than 50% when the internal pressure of the cavity is 25 kPa, more than 100% at 70 kPa, and more than 400% when the internal pressure is 170 kPa. The scale bar represents the equivalent displacement of the model deformation in the FEA results, and its unit is millimeter.
for phase transition is encapsulated in the soft robotics’ cavity, with an outer diameter of 30 mm and a wall thickness of 6 mm (to avoid leakage of the capsuled liquids). When the temperature is elevated over the boiling point, the capsuled liquid could gradually transit to the vapor phase, inducing the volume expanding. To reduce the driving temperature thus energy consumption and the impact on the underwater environment and aquatic animals, a nonflammable and nontoxic liquid with a low boiling point of 34 °C (3M™ Co. Ltd., Novoc™ 7000) was adopted as the working fluid. As the silicones we used are gas-permeable materials, we complete the performance test of the prototype within two days to ensure the stability and accuracy of characterization. To make our proposed submersible soft-robotic platform work in a wide range of applications, we are trying to solve this problem in different ways in further research, and we believe the durability of this submersible soft-robotic platform will be improved.

During the driving process, the capsuled liquid gradually transitions from liquid to vapor and must take one of the three states: liquid, liquid/vapor coexistence, and vapor. In a previous study, it is shown that the rapid volume expansion occurs in the state of liquid/vapor coexistence, which is used as the driving regime for hovering manipulation. The liquid–vapor phase transition process is determined by the temperature and the stress of the superelastic shell and the relation between the vapor pressure and temperature is shown in Equation (1).

\[ P = \frac{152}{20.265} \cdot 10^4 \cdot \frac{1}{T} \]  

(1)

where \( P \) is the vapor pressure (Pa), \( A \), \( B \), and \( C \) are component-specific constants, and \( T \) is the temperature (°C). For Novoc 7000, Equation (1) can be transformed into Equation (2).

\[ \ln(P[Pa]) = 22.978 - \frac{3548.6}{T[K]} \]  

(2)

The values of 22.978 and 3548.6 are constants related to the liquid–vapor phase change material that was provided by 3M™ Co. Ltd.

During actuation, the volume change of the soft-robotic platform is determined by the internal pressure and the stress of the deformed chamber shell, which are directly related to the temperature. To reveal the relationship of volume change versus temperature for depicting the range of buoyancy control, a finite element model for deformation analysis (Abaqus/CAE) is established, as shown in Figure 1b, Note 1 and Video 1, Supporting Information. The simulation results show that the volume increment can be more than 50% when the internal pressure of the cavity is 25 kPa, more than 100% when 70 kPa, and more than 400% when the internal pressure is 170 kPa. The experiments show that the volume increment of about 370% can be achieved at the heating temperature of 55.6 °C, which is shown in Note 2, Supporting Information. This proves the excellent load capacity and large-scale buoyancy control ability of the soft-robotic platform we proposed. The platform can provide a reversible buoyancy range far beyond that provided by reported soft underwater robotics and has the ability to realize large weight bearing with light self-weight.\[12,14,20\]

To realize hovering, a control system is constructed, as shown in Figure 2. The driving and control system of the submersible soft-robotic platform includes a direct current (DC) power supply, proportional–integral–derivative (PID) controller, solid-state relay, flexible polyimide (PI) heating film, and the thermocouple. This temperature control system with feedback adjustment can realize fast response and precise temperature control. By comparing the deviation \( e(t) \) between the set temperature \( n(t) \) and the measured temperature \( y(t) \), the PID controller controls on/off of the solid-state relay as well as the heating process by the control signal from the embedded fuzzy PID control algorithm. The control schematic is shown in Figure 2a, and the differential equation of PID control is shown in Equation (3).\[21\]

\[ u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \]  

(3)

where \( e(t) \) is the control input and \( e(t) = n(t) - y(t) \) (the deviation between controlled value and given value), \( y(t) \) is the output of the system, \( n(t) \) is the set temperature, \( u(t) \) is the output control signal, and \( K_p, K_i, K_d \) are the scale factor, integral coefficient, and differential coefficient, respectively.

When controlling the temperature inside the cavity of the soft-robotic platform, due to the hysteresis of the temperature response when heating and the inertia of the floating/diving movement driven by buoyancy, it is necessary to stop heating before the temperature reaches the set value to ensure the stability and accuracy of the temperature and motion control, and the same goes for the cooling process. As shown in Figure 2b, after the self-tuning of fuzzy PID control, the temperature inside the cavity of the soft-robotic platform can quickly stabilize within the set range. By analyzing the test data in experiments, we found that it takes a fluctuation period of about 50 s after heating begins to achieve a stable temperature and the required buoyancy.

To elucidate the buoyancy control capability of the submersible soft-robotic platform, the buoyancy force and floating height at various temperature are evaluated, as shown in Figure 3a. The heating temperature exhibits a significant impact on the response speed of the submersible soft-robotic platform; to achieve 30% of the floating height, it takes 30 s at 70 °C, 20 s at 80 °C, and only 15 s at 90 °C. It should be noted that the depth of the water tank we used is 600 mm, and the water depth is 340 mm in the experiments described in Figure 3a. In the following hovering experiments, the water depth is increased to 450 mm to investigate the hovering ability in specific depth.

To further test the hovering ability of the submersible soft-robotic platform, the temperature dependence of the buoyancy at a fixed depth is investigated. Figure 3c shows the schematic diagram of the experimental setup for measuring buoyancy. The soft-robotic platform was sunk into a water tank, which was connected to a forcerometer with an accuracy of 0.1 mN (HLD-2N, HANDPI, China) through a fixed pulley by a thread. The buoyancy force \( F_{\text{Buoyancy}} \) produced by a fully submerged soft robotic is mathematically governed by the Archimedes’ Principle (4).

\[ F_{\text{Buoyancy}} = \rho_{\text{water}} \cdot g \cdot V_{\text{soft-robotic}} \]  

(4)
where $\rho_{\text{water}}$ is the density of water, $g$ is the gravitational acceleration, and $V_{\text{soft-robotic}}$ is the total volume of the submersible soft-robotic platform.

During driving, as temperature increases, the liquid–vapor transition would drive the volume expansion ($V_{\text{soft-robotic}}$ increasing) of the head of the soft-robotic platform, inducing the increase of $F_{\text{Buoyancy}}$. Considering that there exists friction at the fixed pulley in our experiment, $F_{\text{Buoyancy}}$ could be obtained by the force balance of the testing system, demonstrated by Equation (5).

$$F_{\text{Buoyancy}} = G + F_{\text{Pull}} = m \cdot g + F_{\text{Test}} + f$$

where $G$ is the gravity of the submersible soft-robotic platform, $F_{\text{Pull}}$ is the force provided by the thread, $m$ is the mass of the system, $F_{\text{Test}}$ is the force measured by the forcemeter, and $f$ is the friction at the pulley.

The friction $f$ could be deduced at the initial test ($30^\circ$C) before heating: the self-weight is 72.2 g, the volume is $85 \times 10^{-6}$ m$^3$, and the tensile force of 0.0140 N is measured by the forcemeter; thus, $f = 0.11$ N. During driving by heating, the temperature of the soft-robotic platform would elevate, and the heat conduction to the ambient water environment is inevitable, which induces more energy consumption and may affect the surrounding state.

To clarify this effect, the heating temperature is set at 65°C, and it is found that the surrounding temperature (the area within $1 \times 10^{-3}$ m$^3$ around the soft-robotic platform) is elevated by less than $0.3^\circ$C, whose effect to the underwater environment could be neglectable. It should be noted that, by elevating the heating temperature, the driving capacity could be further enhanced; the heat conduction to the surroundings, however, would increase as well. Therefore, on the basis of a reasonable temperature
elevation in surroundings, the driving capacity could be enhanced by elevating the heating temperature.

Figure 3b shows the variation of the output buoyancy force as the temperature inside the cavity increases to 65 °C. It reveals that the submersible soft-robotic platform can generate a buoyancy force of 0.93 N (131% of its self-weight) at a low heating temperature of 63 °C with only 5 mL of low-boiling-point liquids capsuled inside and achieve more than 40% of the total buoyancy change rapidly within 55 s. Compared with previous studies, i.e., soft swim-bladder robots driven by dielectric elastomer can only generate a buoyancy of less than 0.06 N with an applied high voltage of 10 kV, and the swim bladder using dual dielectric elastomer can only generate a buoyancy of less than 0.06 N with an applied high voltage of 10 kV, and the swim bladder using dual dielectric elastomer membranes can only generate a buoyancy of 0.49 N and a volume increment of 3%,[13,14] the generated buoyance force in our study is much larger and effective. It is worth noting that when the temperature increased rapidly from 30 to 56 °C in 36 s, as shown by the dotted line in Figure 3b, the buoyancy of the submersible soft-robotic platform increases less than 8%. As the temperature tended to be stable, the buoyancy first increased linearly with a slope of 0.364 mN s °C and then also tended to be gentle when it was about to reach its maximum buoyancy. This not only proves that the volume change by liquid–vapor phase transition has a hysteresis to temperature variation, but also exhibits excellent linearity of buoyancy control ability. This excellent characteristic may provide a new way to support high-precision buoyancy control in the development of the submersible soft-robotic platform. In Figure 3b, when heating is stopped, the buoyancy drops significantly while the temperature remains unchanged, which could be attributed to the latent heat released during the vapor–liquid phase transition. Obviously, under the guidance of the mechanism mentioned earlier and finite element analysis (FEA) simulation, by controlling the heating temperature or adoption of more low-boiling-point working liquids into the cavity of the soft-robotic platform, the buoyancy force and its control capabilities could be further improved.

Further, to reveal the hovering performance of the submersible soft-robotic platform, a series of tests were conducted, and the results are shown in Figure 4 and Video 2, Supporting Information. To investigate the hovering ability, the prototype of the submersible soft-robotic platform is designed and prepared, with self-weight of 29 g, shell thickness of 3 mm, and 15 mL working liquid encapsulated inside the cavity. As shown in Figure 4b, first, we set the heating temperature at 50 °C, the soft-robotic platform obtains a buoyancy force (around 0.30 N) more than its self-weight and floats up to the surface of water; and then, the heating temperature is dropped to 39 °C (around 0.28 N in buoyancy force); the soft-robotic platform starts to sink due to its weight over the buoyancy force and finally achieves a
fixed depth of suspension at a depth of 180 mm. By the PID controller for temperature control, a high-precision hovering depth, with a fluctuation within 17.42 mm, is achieved. By reducing the shell thickness of the prototype, the temperature for hovering could be reduced, which is more friendly to the environment.

For a hovering underwater robot, it is deserved to investigate its loading capacity. In our experiments, we added the same weight to each tentacle of the bioinspired submersible soft-robotic platform, and the total weight of the load is 8 g, which is 1.6 times of the weight of the low-boiling-point liquid (Novec 7000) capsuled inside the cavity. As shown in Figure 4a and Video 3. Supporting Information, when the heating starts (the heating temperature is set at 60 °C), the soft-robotic platform gradually rises due to the increase of buoyancy that is caused by volume change. The internal temperature varies within 1.5 °C, which is 2.5% of the heating temperature, verifying the stability of the temperature control system. It is found that the curve of the floating height versus time is nearly parabolic, which proves the continuity and stability of the buoyancy generated by the liquid–vapor phase transition. At the same time, we found that even with a low driving temperature (<60 °C), the submersible soft-robotic platform can achieve vertical movement quickly, such as floating up for 450 mm in 18 s, which is 18 times of its main body length. The bioinspired soft-robotic platform showed excellent stability during the floating process, and this may be conducive to the stable and efficient work of the functional components (such as camera and sonar) loaded on the platform.

We have proposed a bioinspired submersible soft-robotic platform based on the liquid–vapor phase transition, which holds the advantages of non-noisy and large-scale buoyancy control capability. Through the heating and temperature regulating by the embedded flexible PI heating film and thermocouple, this submersible soft-robotic platform demonstrates effective rise-and-sink motion in water with the large reversible volume change and can generate a buoyancy force of 0.93 N (131% of its weight) at a low heating temperature of 63 °C with excellent linearity and achieve more than 40% of the total buoyancy change rapidly within 55 s while floating up more than 450 mm (18 times of its length) in 18 s. Also, the response speed of the buoyancy change can be increased by 50% when the heating temperature is increased by 20 °C. This bioinspired submersible soft-robotic platform shows an excellent stability and loading capacity even at a low heating temperature (60 °C), and the heating temperature had no significant effect and damage to the surrounding water environment. Although the prototype used in our research is powered by cable and external power supply, it is necessary to integrate the control and energy supply units on the submersible soft-robotic platform, and this can greatly expand the application range of this submersible platform. This bioinspired submersible soft-robotic platform with non-noisy and large-scale buoyancy control capability addresses the critical challenges in the design and driving method of soft underwater robotics and AUVs and suggests a feasible approach to develop biofriendly, high-reliability, and autonomous underwater robotic platforms with hovering ability. This bioinspired submersible soft-robotic platform holds promise in many fields, ranging from aquatic environment surveys to biological observation and oil spill examinations.

Experimental Section

Temperature Controlling Method: All these prototypes of the soft-robotic platform were heated by a flexible PI heating film (12 V, 5 W) embedded in
the cavity, and the temperature inside the cavity was controlled by the PID temperature controller (ANTHONE, Xiamen, China) with a thermocouple (K-type).

Characterization of the Submersible Soft-Robotic Platform: The driving test of the soft-robotic platform was conducted in a water tank made of an acrylic plate with a size of 300 × 300 × 600 mm. We measured the floating height of the platform by processing the photos taken by the digital camera (Nikon D750) and Samsung S20 using ImageJ. We measured the magnitude of buoyancy using a precision forcemeter with an accuracy of 0.1 mN (HLD-2N, HANDPI, China).

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.

Author Contributions
W.J. and J.H. conceived the concept and wrote the manuscript. J.H., H.Z., and B.L. conducted the experiments and the mechanical analysis. W.J. and L.W. guided material fabrication. W.J. and H.L. directed the project. All authors analyzed and interpreted the data.

Keywords
bioinspired soft robotics, buoyancy controls, liquid–vapor phase transitions, underwater soft-robotic platforms, variable buoyancy systems

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