Electromechanical Control and Stability Analysis of a Soft Swim-Bladder Robot Driven by Dielectric Elastomer

Compared to the conventional rigid robots, the soft robots driven by soft active materials possess unique advantages with their high adaptability in field exploration and seamless interaction with human. As one type of soft robot, soft aquatic robots play important roles in the application of ocean exploration and engineering. However, the soft robots still face grand challenges, such as high mobility, environmental tolerance, and accurate control. Here, we design a soft robot with a fully integrated onboard system including power and wireless communication. Without any motor, dielectric elastomer (DE) membrane with a balloonlike shape in the soft robot can deform with large actuation, changing the total volume and buoyant force of the robot. With the help of pressure sensor, the robot can move to and stabilize at a designated depth by a closed-loop control. The performance of the robot has been investigated both experimentally and theoretically. Numerical results from the analysis agree well with the results from the experiments. The mechanisms of actuation and control may guide the further design of soft robot and smart devices. [DOI: 10.1115/1.4037147]

1 Introduction

Robots have played essential roles in modern society because of their high output force, controllability, and precision. However, most robots are developed based on hard materials, which have limitations in energy utilization, adaptability, and human–robot interaction. Soft robots attract growing attention [1–6] because of their unique advantages over conventional rigid robots, including large actuation, high adaptability, and high compatibility with human. Aquatic creatures inspire the design of soft robots due to their large fraction of soft body and high agility [7–12]. The increasing importance of ocean missions generates the demands for developing high-performance aquatic soft robot.

An increasing number of researchers focuses on developing underwater robot systems for various missions, such as marine environment monitoring, exploration of marine resource, and investigation of underwater creatures [13]. Conventional aquatic robot driven by hard components such as electric motors and electromagnetic actuators [14–18] has limitations in the field operation due to their high noise and low adaptability. Soft active materials, such as ionic conducting polymer film [19], shape memory alloys [20,21], and ionic polymer metal composites [22–24], can be used as artificial muscles to drive the aquatic soft robots. These robots have limitations because of the low energy density [20,21], small deformation [20,21], and slow response [19,22–24]. Achieving fast response, high energy density, and large deformation, dielectric elastomer (DE) [25–27] stands out among various stimuli-responsive materials. Recently, several groups have developed aquatic soft robots driven by dielectric elastomer. Zhu and coworkers [1] have designed a jellyfish robot, Li et al. [28] have designed a Manta-ray robot, and Anderson et al. [29] have designed an artificial muscle actuator for a robotic fish. Michel and coworkers [30] have designed fishlike propulsion of an airship.
Those robots show good performance in fast response, large actuation, and environmental adaptability. However, those robots show difficulty in controllability and robustness, and no control algorithm has been applied to any of them. In this paper, we focus on designing an aquatic soft robot driven by a bladder-shaped DE actuator. Onboard system for power, control, and communication is developed. Control algorithm has been applied to tune the operation depth and stabilize the movements of the robot.

This paper is arranged as follows: Section 2 has discussed the mechanical design and actuation mechanism of the robot. Section 3 presents the process and results of the underwater experiments. Section 4 derives an analytical model for the DE actuator. The analytical results are compared with the experimental measurements. Section 5 illustrates stability of the system with and without control. The performance of the robot has been evaluated.

2 Mechanical Design and Movement Mechanism of the Robot

Inspired by the structure and floating mechanism of the swim-bladder, we design the artificial swim-bladder robot by using DE membrane (3M™ VHB™) as the artificial muscle. The detailed fabrication process is shown in Fig. 1. The artificial muscle laminate (Fig. 1(a)) consists of a thin DE membrane coated with carbon grease. We stack the 3M™ VHB™ 4910 and 4905 membranes together to make DE membrane with various thicknesses (0.5 mm, 1 mm, 1.5 mm, 2 mm, and 2.5 mm) in the experiments. Then, the DE membrane is biaxially prestretched (3 × 3) and fixed on the open end of an acrylic chamber. The size of the acrylic chamber is 6 cm in diameter and 10 cm in height (Figs. 1(b) and 1(c)). Then, we seal the chamber and add counterweight to balance the buoyant force (Fig. 1(d)). Air is pumped into the chamber deforming the DE membrane into a balloon shape (Fig. 1(e)).

Figure 2 shows the actuation mechanism of the swim-bladder robot. While the carbon grease serves as electronic conductive electrode, the surrounding water is utilized as the ionic electrode. Despite the low electrical conductivity of the water (~50 mS/m), it is sufficient to serve as an effective electrode [28], which will be evidenced later in the context. Without applying a voltage, the DE membrane is deformed by the pressure difference and maintains an equilibrium state (the inflated state). Figures 2(a) and 2(c) show the inflated state in schematic and experimental image. When a voltage is applied (Figs. 2(b) and 2(d)), positive and negative charges accumulate on both sides of the DE, inducing Maxwell stress [31] and deforming the DE membrane (the actuated state). The actuation of the DE membrane changes the volume and the buoyant force of the DE balloon. As a result, the position of the swim-bladder robot varies.

3 Experiments

The goal of this study is to achieve a controllable artificial swim-bladder robot with onboard power and control. The experimental setup includes a DE membrane, carbon grease, an acrylic bottle, an onboard power source which is named as “Epod,” and a pressure sensor circuit (Fig. 3). The system in Epod is controlled by an eight-pin microcontroller unit (MCU) to tune the voltage amplitude. The high voltage amplitude is adjusted by pulse-width modulation duty cycle. Pressure sensor circuit is powered by a low voltage battery (3.7 V) with a pressure sensor connecting to the MCU. Two circuits exchange data via two 2.4G ZigBee wireless modules. Epod tunes the voltage amplitude according to the pressure signal sent by pressure sensor circuit. Besides, a computer can communicate with Epod via ZigBee in order to display and monitor real time data. Figure 3(d) plots the experimental data of pressure increment as a function of voltage, which is collected by the pressure sensor.

The floating performance of the robot is affected by the initial volume of the DE balloon, which can be tuned by pumping air into the chamber with an initial pressure. Figure 4(a) plots the experimental data of the buoyant force increment as a function of voltage with various initial pressures. The thickness of DE membrane is 2 mm. The depth is 25 cm. When the membrane starts actuation from a hemisphere shape without voltage (Fig. 4(e), and the initial inner pressure is about 108 kPa), the device achieves the largest variation of the buoyant force (voltage from 0 to 10 kV) than the other conditions with various initial shapes of the balloon (Figs. 4(b)–4(g)).

In the experiment, we performed a series of experiments to evaluate the performance of the swim-bladder robot with various thicknesses of DE membrane (Fig. 5). Figure 5(a) plots the experimental data of volume increment as a function of voltage. Figure 5(c) illustrates the experimental data of buoyant force increment.
as a function of voltage. The buoyant force was measured by a force sensor connected to the swim-bladder robot (the force difference before and after the actuation of the DE membrane). Under the same voltage value, thinner membrane provides larger buoyant force change before electrical breakdown (the black cross). However, thicker membrane could endure higher voltage and could finally attain larger change of buoyant force. The maximum voltage value is limited under 10 kV due to the limitation of the instrument.

The change of buoyant force of the robot is affected by both voltage and depth. The change of buoyant force could be represented by the total volume of the DE membrane and the chamber. Figure 5(c) plots the experimental data of total volume as a function of both voltage and various depths. The results show that there is no interconnection between the voltage-induced volume expansion and depth-induced volume expansion. This behavior guarantees that the linear control is possible for the floating of the robot.

To further investigate the behaviors of the robot, we have developed an analytical model (Sec. 4). To prove the validity of the model, we used MATLAB to solve the implicit function. Figures 5(b) and 5(d) show the volume–voltage relation and the buoyant force–voltage relation with various thicknesses of DE membrane (corresponding to the experimental results in Figs. 5(a) and 5(c)). Figure 5(f) shows the analytical results of the pressure–voltage relation with various depths (corresponding to the experimental results in Fig. 5(e)). The analytical results qualitatively agree with the experimental measurements.

We use an independent driving power source to drive the robot in order to replace the bulky high voltage power source. Figure 6 plots the experimental data of the voltage-induced volume expansion as a function of the control signal. There is a positive correlation between control signal and actual voltage. To keep the swim-bladder robot at a specific depth z, an on–off control strategy is used: the output is set either on or off according to the air pressure. When the output is turned on, the power source applies a control signal (with the value of 15,000). Before the control process, the system is calibrated with the following five steps:

1. Place the robot at a certain place in the water tank with a depth of \( z_0 \).
2. Measure the air pressure \( P_{\text{off0}} \) without applying voltage.
3. Measure the air pressure \( P_{\text{on0}} \) after turning on the voltage.
4. Calculate the variation of the air pressure \( \Delta P \) when the robot is placed 1 cm deeper in the water.
5. Calculate two pressure values \( P_{\text{on}} \) and \( P_{\text{off}} \) (the desired pressure when the robot stays at a depth of \( z \)).

\[
P_{\text{off}} = P_{\text{off0}} + (z - z_0) \cdot \Delta P \quad (1)
\]
\[
P_{\text{on}} = P_{\text{on0}} + (z - z_0) \cdot \Delta P \quad (2)
\]

Figure 7 is the flow chart of the algorithm. The voltage needs to be turned off if the robot rises too high, with a pressure lower than \( P_{\text{on}} \). The voltage will be turned on when the robot drops too low, with a pressure higher than \( P_{\text{off}} \).

The algorithm controls the robot to stay at a certain depth in a short period. In the experiment, we place the robot at the bottom of the water tank with the initial depth of 25 cm. The robot takes about 25 s (nearly four cycles of control) to reach the convergence at the designated position (depth \( z = 15 \) cm.). The robot stays at the designated depth, with the control signal oscillating (on and off) at a period about 1.17 s. (Fig. 8).

In the experiment, the robot’s maximum variation of buoyant force is 0.046 N when the voltage is 10 kV (DE membrane with two stacked VHB-4910). The mass of the robot is 0.45 kg. The maximum acceleration is around 0.1 m/s\(^2\). During one operation of the robot, the average speed of ascending reaches 3.5 cm/s.

4 Theoretical Analysis

We build up a mechanical model to analyze the swim-bladder robot and to illustrate the floating mechanisms of robot driven by...
Fig. 3 The onboard power source (Epod) and the method of control and communication. (a) Onboard high voltage source is powered by a lithium–ion battery (3.7 V) with fly back topology to achieve small size, high voltage, and isolation. The circuit and battery were sealed in a plastic tube as the Epod. (b) The robot with an Epod assembled onboard. (c) The relation of control, communication, and the actuation of the robot. (d) The data (collected from the pressure sensor) of pressure and voltage relation with various voltages and membrane thickness.

Fig. 4 Buoyant force increment as a function of voltage, and the effects of initial inner pressure. (a) The relation of buoyant force increment and voltage with various initial inner pressures. (b)–(g) The inflated balloonlike shapes of the DE membrane with no voltage and different initial pressures of 106.0 kPa, 107.0 kPa, 107.5 kPa, 108 kPa, 108.5 kPa, and 109.0 kPa.
the actuation of DE membrane. The DE membrane is modeled using the nonlinear theory of Suo [32]. Figure 9(a) illustrates a membrane of DE sandwiched between two compliant electrodes (the reference state). The membrane is subject to neither force nor voltage, and has a radius of $R$ and a thickness of $H$. Under the prestretched state, the membrane deforms with the radius of $r$ and the thickness of $h$. We simplify the DE balloon as a spherical shape. $W_{\text{stretch}}(\lambda_1, \lambda_2)$ is the free energy associated with the stretching of the elastomer membrane. The deformation of the membrane is induced by the equal-biaxial Maxwell stresses with the magnitude.

**Fig. 5** The experimental results showing the relation of volume and buoyant force with various voltages and membrane thickness, the effect of depth, and their corresponding numerical results from MATLAB simulation. (a) The relation of volume and voltage. (b) The numerical results of volume–voltage corresponding to the experimental results in (a). (c) The relation of buoyant force and voltage. (d) The numerical results of buoyant force increment–voltage corresponding to the experimental results in (c). (e) The relation of pressure and voltage when the robot is anchored at the certain depth from 25.0 cm to 12.5 cm, respectively. (f) The numerical results corresponding to the experimental results in (e).
of $\varepsilon E^2$, where $\varepsilon$ is the permittivity of the elastomer and $E$ is the electric field applied through the membrane [33–40]. We can adopt the Gent model [41] to describe the parameter $W_{\text{stretch}}$

$$W_{\text{stretch}} = -\frac{\mu J_{\text{lim}}}{2} \log \left( 1 - \frac{J_{\text{lim}}^2 + J_{\text{lim}}^2 + J_{\text{lim}}^2}{J_{\text{lim}}} \right)$$

(3)

where $\mu$ is the small-strain shear modulus of the elastomer and $J_{\text{lim}}$ is the material parameter related to the stretch limit.

In the absence of any applied loads, the state as shown in Fig. 9(a) is considered as a state of reference. We define the coordinate’s origin at the center, and the $z$ axis is normal to the plane. Any particle of radius $R$ at the reference state may move to a place with coordinates $r$ and $z$ at the current state when the membrane is subject to pressure $p$ and voltage $\Phi$ (see Fig. 9(d)), where we assume that the membrane is of an axisymmetric shape.

With the boundary condition and initial value, we can get the volume enclosed by the membrane

$$V = \int_0^A 2\pi r \frac{dz}{dR} dR$$

(4)

where $A$ is the radius of the membrane at the reference state (Fig. 9(a)), $r$ and $z$ are all the functions of $R$, and the equations are partial differential equations, which lead to the insolubility of the analytical results [42].

We simplify the analytical model and consider the DE balloon as a hemisphere. With the changing of air pressure or membrane...
tension, the radius of the DE balloon changes without changing its spherical shape (Figs. 9(e) and 9(f)). When the robot reaches the equilibrium state, the relation between inner pressure in DE balloon, the external pressure of water, and the stress of the DE membrane can be expressed as

\[ 2\pi R_h \cdot \left( \sigma_0 - \epsilon \left( \frac{\Phi}{h} \right)^2 \right) = \pi R^2 (P_{\text{inner air}} - P_{\text{water}}) \]  

(5)

where \( R_h \) is the radius of the membrane sphere, \( h \) is the thickness of the membrane, \( P_{\text{inner air}} \) is the inner pressure of the robot, and \( P_{\text{water}} \) is the pressure of the water. \( \sigma_0 \) is the longitudinal and latitudinal stresses. Since the spherical DE membrane is thin, we neglect the stress normal to the membrane in the equation. We assume that the material is incompressible, and the membrane is equal biaxially stretched with a spherical shape. The stretches of the membrane satisfy that

\[ \lambda_1 = \lambda_2 = \lambda, \quad \lambda_3 = \frac{1}{\lambda_1 - \lambda_2} = \frac{1}{\lambda^2} \]  

(6)

\( \lambda_1 \) is the longitudinal stretch, \( \lambda_2 \) is the latitudinal stretch, and \( \lambda_3 \) is the stretch in the thickness direction of the membrane. Then, \( \sigma_0 \) can be expressed as

\[ \sigma_0 = \lambda_1 \frac{\partial W_{\text{stretch}}(\lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_1} = \frac{\mu \cdot (\lambda^2 - \lambda^{-4})}{1 - (2\lambda^2 + \lambda^{-4} - 3)/J_{\text{lin}}} \]  

(7)

By comparing the experimental results with the model, we adjust the parameters to \( \mu = 45 \text{kPa}, J_{\text{lin}} = 270, \) and \( \epsilon = 4.16 \times 10^{-11} \text{ F/m} \) [25].

Then, we simplify Eq. (5) to

\[ \left( \frac{\mu \cdot (\lambda^2 - \lambda^{-4})}{1 - (2\lambda^2 + \lambda^{-4} - 3)/J_{\text{lin}}} - \epsilon \left( \frac{\Phi}{h} \right)^2 \right) \cdot 2 \frac{H}{\lambda^2} \]  

\[ = \frac{A \lambda}{\sqrt{2} \lambda_0} (P_{\text{inner air}} - P_{\text{water}}) \]  

(8)

where \( A \) is the radius of the acrylic chamber, and \( \lambda_0 = 3 \) is the pre-stretch ratio from Figs. 9(a) and 9(b).

5 Control and Instability of the System

Assume that at a moment, the whole robot is in an equilibrium state with no voltage applied, and the gravity equals to the buoyancy. The internal pressure in DE balloon, the external pressure of water, and the stress of the DE membrane satisfy that

\[ 2\pi R_h \sigma_0 = \pi R^2 (P_{\text{inner air}} - P_{\text{water}}) \]  

(9)

As the amount of the gas in the chamber is fixed, we assume that the temperature does not change during the process. The pressure and volume of the robot under the initial and the current states satisfy the Ideal gas law

\[ P'_{\text{inner air}} V' = P_{\text{inner air}} V \]  

(10)

where \( P'_{\text{inner air}} \) and \( V' \) are the inner pressure and gas volume of the current state, respectively. When there is a disturbance to the robot causing a change of depth \( \Delta z \) (as shown in Fig. 10(a)), the water pressure variation due to the change of depth can be expressed as

\[ \Delta P = P'_{\text{water}} - P_{\text{water}} = -\rho g \Delta z \]  

(11)

As a consequence, the external pressure becomes smaller than the inner pressure. The DE membrane expands with a larger volume, decreasing the inner pressure until the system reaches a new equilibrium state. Assume that stress of the DE membrane remains constant approximately

\[ P'_{\text{inner air}} - P'_{\text{water}} = P_{\text{inner air}} - P_{\text{water}} = 2\pi R_h \sigma_0 \]  

(12)

\[ \Delta V = P_{\text{inner air}} - P'_{\text{inner air}} V = -\frac{\Delta P}{P_{\text{inner air}}} \]  

(13)

where \( \Delta V \) is the change of the volume. According to Newton second law

\[ a = \frac{F_{\text{buoyancy}} - G - k v}{M} = -\frac{\Delta P}{P_{\text{inner air}}} \times \frac{\rho g V}{M} - K v \]  

(14)

where \( G \) is the gravity force, \( F_{\text{buoyancy}} \) is the buoyant force after the change, \( a \) is the acceleration of the robot, \( \rho \) is the water density, \( g \) is local acceleration of gravity, \( V \) is the initial volume of the air chamber, \( M \) is the total mass of the robot, and \( k \times v \) presents the approximate fluidic resistance when the robot is at low speed (\( v \) is the speed of robot and \( k \) is the fluidic resistance coefficient). We define \( K = k/M \) as a constant. When a disturbance happens with a small altitude range, \( P_{\text{inner air}} \) approximately equals to \( P'_{\text{inner air}} \)

\[ a = \frac{\rho^2 R^2 V}{P_{\text{inner air}} M} \Delta z - K v = C z - K v \]  

(set \( z_0 = 0 \) )  

(15)

Fig. 10 The schematics of the robot during floating and sinking. (a) \( z \) is the vertical displacement, which can be calculated from the depths of the robot. (b) When the parameters of the system such as weight, initial pressure, and the thickness of DE membrane are fixed, the control method has a limit of operative depth. Only when the robot locates between the upper and lower limits, can the MCU control and stabilize the robot.
where \( C = (\rho^2 g^2 V)/(P_{\text{outer}} \cdot \text{air} M) \) is a constant, determined by the robot’s initial condition.

Let \( z = x_1 \), \( v = x_2 \), and \( a = \dot{x}_2 \). The linear state space model of the system is

\[
\dot{x} = Ax = \begin{bmatrix} 0 & 1 \\ \frac{K}{C} & -K \end{bmatrix} x
\]

(16)

The stability of the system can be investigated by the eigenvalue equation as

\[
\Delta s = |sI - A| = s^2 + Ks - C = 0
\]

(17)

\[
s_{1,2} = \frac{-K \pm \sqrt{K^2 + 4C}}{2}
\]

(18)

According to the first method of Lyapunov, as one of the eigenvalues of \( s \) is positive, the system is unstable. Figure 11(a) shows the block diagram of the unstable system.

In order to make the robot be able to stay at a designated depth, the system needs to be stable with a convergent output. We apply an on–off control to the system. Figure 11(b) shows the block diagram of the on–off control system. The sampling rate is 20 Hz.

The water pressure is measured by the pressure sensor and transformed to the relative displacement of the robot, compared with certain value according to the system’s condition and control voltage applied on the DE membrane. The stability is examined by the voltage relaxes the DE membrane and decreases \( \sigma \), and consequently changes the acceleration of the robot.

In order to analyze the performance of swim-bladder robot, we take the robot condition (the curve in Fig. 5(e)): thickness: 2 mm; initial pressure (above water): 108.0 kPa; initial depth: 25 cm) as example, the maximum buoyant force is 0.046 N when the voltage is 10 kV. The mass of the robot is 0.45 kg. The maximum acceleration is around 0.1 m/s². The robot’s operation range is the region that the MCU can control the system to converge at a certain depth, which has a limitation. The upper bound of the controllable depth is the depth that the robot starts to float up without applying voltage on DE membrane. The lower bound is the depth that the robot starts to sink down when the voltage already reaches the maximum value (10 kV in our experiment).

As shown in Fig. 10(b), we assume that the change of inner pressure is \( \Delta P \) (voltage: 10 kV)

\[
\Delta z = \frac{\Delta P}{\rho g}
\]

(19)

According to the experimental data, the controllable range between upper bound and lower bound \( \Delta z \) is around 21.8 cm. As shown in Fig. 3(d), when the thickness of the membrane increases, the maximum value of \( \Delta P \) increases. So the controllable range is larger when the membrane is thicker. If the maximum voltage of the apparatus could be higher and the membrane could be thicker, the controllable range could be larger. However, the position of upper bound and lower bound is decided by the balance weight.

6 Conclusions

In summary, we have developed an artificial swim-bladder robot, which can be controlled by the actuation of an inflated DE membrane. The air chamber, covered with the DE and filled with air, can provide buoyant force to maintain the robot balanced. In addition to the wireless mobility, the robot possesses other notable attributes including long endurance, low noise, and precise control. The robot is driven by the DE membrane with applied voltages, which tune the pressure, total volume, and the buoyant force of the robot. Stability analysis shows that the system is unstable, and the robot cannot maintain its depth without control. The simple on–off control can actuate the DE membrane with desired shape to balance the buoyant force and maintain the position of the robot in designated depths. The thickness and the initial inflated shape of the DE membrane can affect the controllable operating range of the robot. The robot achieves relatively high performances in aspects such as buoyant force variation, speed, and acceleration. The robot can either function as a robotic system itself or be attached on other robotic systems (robotic fish for example) as a controllable floating module. The structural design and the control principles of this robot may guide the further design of aquatic soft robot and pressurized soft actuators.

Funding Data

- National Natural Science Foundation of China (11321202, 11432012, 11572280, and U1613202).
- China Association for Science and Technology (Young Elite Scientist Sponsorship Program).

References


