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# Modelling of Buoyancy Based Actuation of an Inflatable Underwater Soft Robot

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**Abstract.** This paper presents a novel actuation method to change the buoyancy of an underwater soft robot by pumping denser and less dense liquids, than the liquid the robot is immersed in, into the robot to actively change the mass of the robot and cause it to experience a change in buoyancy. The technological research gap lies in the method of pumping lighter and heavier fluids into a soft robot to cause it to experience a change in mass and depth, which has not been explored before to the best of the author’s knowledge. An analysis of the forces that are placed on the robotic system and the necessary equations to determine the force produced by a solution with a particular ratio of solute to solvent are presented. Preliminary experiments were conducted to test the buoyancy-based actuation method discussed in this paper by building a two link, soft, inflatable robot arm. This robot was shown to change the floatation height of its links when denser fluid was pumped into its links.

**Keywords:** Depth controllable soft robot · Buoyancy controllable soft robot · Buoyancy actuated soft robot · Underwater soft robot arm

## 1 Introduction

### 1.1 Background

There are three common types of robots that are deployed underwater: Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and gliders. ROVs are robots for marine exploration, that are tethered to a support ship and are controlled by a human operator [17]. ROVs are used in a range of applications including archaeological discovery [23], inspection of oil rig platforms [19] and offshore wind farms [22], preventing marine fouling [3], biological exploration and sample collection [4], underwater mine detection and disposal [15], and search and rescue [7]. Despite their wide array of uses, these robots are limited in that they are unable to operate autonomously and rely on a highly trained human operator to control them. They also require a ship to be tethered to, which needs a crew, which is expensive. Furthermore, ROVs have problems

due to visibility being limited and communication being slow underwater [9]. This makes control especially challenging as the ROV system is working in real time and ideally feedback from its sensors need to be processed immediately as the environment can change around the ROV quickly.

Autonomous underwater vehicles (AUVs) are another type of marine robot. They are autonomously controlled and untethered [16] [5]. Gliders are a subset of AUVs that move through adjusting their buoyancy [18]. Being untethered means that a support ship is not required and being autonomously controlled enables these robots to be in operation for long periods of time as a human operator is not required. Like ROVs, AUVs and gliders are used in a range of applications including inspecting infrastructure [10], marine surveying [2], oceanography and biological sample collection [24].

Despite the large number of applications in which these current state of the art underwater robotic systems are used, they all suffer from the drawbacks of being rigid, and large in size and therefore not conformable to their environment. This means that certain underwater environments, such as those that are tight and narrow like coral reefs and underwater cave systems, are difficult for them to move through.

A potential solution to this problem could be through the use of soft robots. These robots have properties that make them desirable for underwater applications including being soft and deformable so that they have the ability to squeeze through narrow openings, but also not cause significant damage to marine structures that they come into contact with, being cheap to manufacture if degradation happens due to the marine environment or if lost at sea, being straightforward to deploy as they are light weight and can be compactly stored, and not greatly affected by pressure changes.

There are an increasing number of soft robots being designed for underwater applications. These include bio inspired robots such as fish [21], stingrays [1] and octopuses [8].

An ability that both soft and hard underwater robots should have is a method to change their buoyancy. There are many methods of achieving buoyancy control in literature.

One method of changing buoyancy is to have a chamber inside the robot that is filled with air that can be compressed to make the robot experience negative buoyancy and expanded for positive buoyancy, as seen in [12], which explored this mechanism for a soft underwater fish. A potential problem with a system such as this is that if the air chamber has a leak, such as from the degradation of sea water over time or from manufacturing defects, air could leak out preventing the robot from being able to move up and down.

Another method of changing buoyancy is to change the angle of dive planes that are located externally on the robot, like that seen in [13]. A potential problem with this mechanism is that if the robot is moving through a tight and cramped environment, such as through a coral reef, the robot's dive planes could become obstructed, preventing or limiting vertical movement.

Another method shown in literature to change buoyancy is to heat wax to cause a change of volume and thus a change in buoyancy [20]. A potential problem with this mechanism is that it could be not possible or require more energy to heat the wax in colder waters.

In this paper, a novel method of buoyancy based actuation is presented. A denser fluid than the surrounding fluid that the robot is in, is pumped into the robot to enable negative buoyancy to occur and for the robot to move downwards towards the ground and a less dense fluid than the surround fluid that the robot is in, is pumped into the robot to enable positive buoyancy to occur and for the robot to move upwards towards the surface of the water. To the best knowledge of the authors, this is the first buoyancy based system that uses fluids of different densities to enable depth change underwater. The work presented builds on our previous work [11], where we looked into a robot that uses lighter fluids to change floatation height in air.

We envisage the robot presented in this paper to be deployed either from a support ship or from an ROV as an arm like [14] and so the pumps necessary for pumping different density fluids can be contained on these vehicles. The robotic system presented in this paper is still underdevelopment, but we intend to use a single premixed denser liquid and a single premixed less dense liquid, which are both capable of applying a single amount of force. To vary the robot's position, precise modulation of these premixed liquids inside the robot is required.

## 1.2 Contributions

The contributions of this paper are as follows:

1. Proving mathematically that changing the composition of a fixed volume solution can result in a change of depth underwater.
2. Providing the essential equations to understand how much force a particular solution can exert based on solute and solvent compositions.
3. Developing a two link soft robotic arm in which the depth position of the links can be changed through pumping denser fluid into them.

## 1.3 Paper Structure

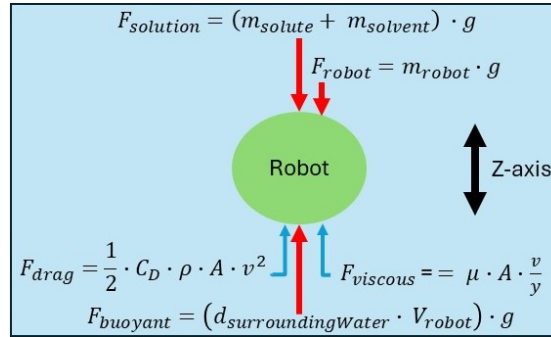
This paper is structured as follows: Section 2 examines the forces that the inflatable robot is under and whether certain forces are more important than others such that they do not need to be considered. Section 3 looks into the forces generated for different compositions of fluids and specifically looks into the use of salt as a solute and distilled water as the solvent for this purpose. Section 4 shows the design and build of a two link soft inflatable robotic arm for use in demonstrating the principles of the buoyancy based actuation method discussed in previous sections. Section 5 presents the results of how the link orientation of the robot arm changes when denser fluids are used to inflate the links. Section 6 concludes the paper and gives some recommendations of future work that should be performed.

## 2 Analysis of the Forces that Act Upon the Robot

Fig. 1 shows the five different forces that act upon the robot underwater. The three larger forces are the controllable downward force  $F_{solution}$ , the upward force  $F_{buoyant}$  and the force produced by the weight of the robot  $F_{robot}$ . There are also two other forces, namely  $F_{drag}$ , and  $F_{viscous}$  that act against the robot's direction of motion. If the robot is moving downwards,  $F_{drag}$ , and  $F_{viscous}$  are applied upwards, as shown in Fig. 1 and is represented mathematically by Eq. 1. If the robot is moving upwards,  $F_{drag}$ , and  $F_{viscous}$  are applied downwards, as shown in Fig. 2 and is represented mathematically by Eq. 2.

### 2.1 Control Force

The controllable solution force,  $F_{solution}$ , is made up of two components, a solute such as a granular substance like sodium chloride and a solvent such as a liquid substance like water and it is the variation of these quantities of components that dictates the amount of force produced that enables the robot to either sink to greater depths or rise to lower depths.



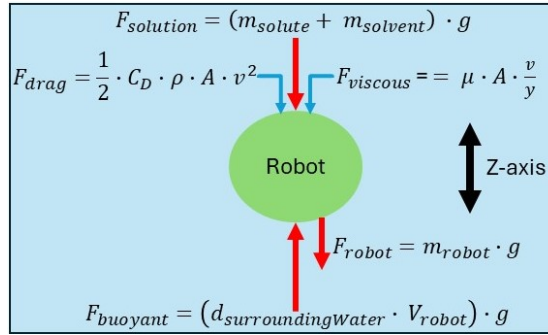
**Fig. 1.** Shows all the forces that are acting upon the robot when the robot is moving downwards

$$F_{resultant} = F_{buoyant} + F_{drag} + F_{viscous} - F_{solution} - F_{robot} \quad (1)$$

$$F_{resultant} = F_{buoyant} - F_{drag} - F_{viscous} - F_{solution} - F_{robot} \quad (2)$$

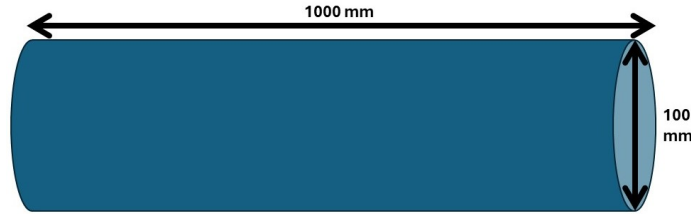
### 2.2 Proving viscous and drag forces are insignificant

Mathematically, it can be proven that drag and viscous forces have negligible affect on the overall resultant force experienced by the robot as we are considering the robot to move at slow velocities such as at 0.01 m/s.



**Fig. 2.** Shows all the forces that are acting upon the robot when the robot is moving upwards.

Considering the first scenario where a cylindrical robot is moving downwards and constructed from PVC with the dimensions length 1000 mm and diameter 100 mm (Fig. 3), it would have a mass around 0.43 grams. If we take an arbitrary mass of solute of 2500 grams and mass of solvent of 7775 grams, then the total downward force is approximately 100000 N. Given the dimensions of the robot, the upward buoyant force is determined to be approximately 76300 N. If  $f_{solution} = 100000N$  and  $f_{buoyant} = 76300N$  are considered to be fixed values and drag force and viscous force are varied, we can observe that from the results seen in Tab.1, that the percentage change in resultant force between scenario 1 where no drag and viscous forces are included and scenarios 2 and 3 where drag and viscous forces are included, is 0.000005%. This shows that viscous and drag force have negligible affect on the robot as there are much larger forces that play a bigger role on the robots overall movement.



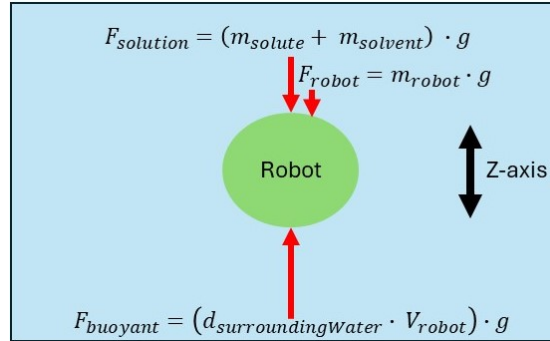
**Fig. 3.** Robot dimensions for proving the negligible affect of drag and viscous forces.

We can therefore not consider these forces when considering the forces that act upon the robot and consider the situation illustrated in Fig. 4 and mathematically represented in Eq. 3.

$$F_{resultant} = (d_{surroundingWater} \cdot v_{robot}) \cdot g - (m_{solute} + m_{solvent} + m_{robot}) \cdot g \quad (3)$$

scenario	Drag Force $F_{Drag}$	Viscous Force $F_{Viscous}$	Resultant Force $F_{Resultant}$	Percentage change
1	0	0	-23700	0
2	0.319	0.00002	-23699.681	0.000005
3	0.319	0.0000003	-23699.681	0.000005

**Table 1.** Showing the Negligible Effect of Viscous and Drag Forces



**Fig. 4.** Shows all the forces that make a significant difference upon the robot's motion.

### 3 Examining the Affect on Varying the Components of the Solution Force

As mentioned in section 2, the solution force  $F_{Solution}$  is formed of two components, the solute and the solvent.

In the robotic system design considered in this paper, it is intended that solutions pumped into the robot would be premixed and so the force these solutions produce would be constant. This is rather than mixing the solute and solvent in the robot itself and having a variable force that can be controlled.

However, it is important to know the force that the premixed solution pumped into the robot can generate for a number of reasons. These include applications where less force is required such as in a fragile environment, applications where more force is required such as in a pick and place task and for considering suitable controllers where change in force needs to be considered to understand how the robot will stabilise at specific depths while reducing the amount of overshooting and undershooting. This section looks into how much force a solution can generate by varying the solute and solvent quantities while maintaining constant volume.

There are two force phases that the solution goes through. The first phase, phase 1, occurs when the solute can be dissolved by the solvent and so the volume does not increase. The second phase, phase 2, occurs when the solute cannot be dissolved by the solvent and the solvent must be decreased to add more solute to maintain a constant volume. It is important to have a constant volume as the robot cannot change volume, so the solution pumped into the robot needs to be of a constant volume.

Phase 1 occurs when the mass of the solute,  $m_s$ , is less than or equal to the maximum amount of solute that is dissolvable in the solvent  $dis_{max}$  and is governed by equation 4.

$$F = (m_s + m_w) \cdot g \quad (4)$$

Where  $m_s$  is the mass of the solute in  $kg$ ,  $m_w$  is the mass of the solvent in  $kg$  and  $g$  is the gravitational acceleration in  $m/s^2$ .

Phase 2 occurs when the mass of solute,  $m_s$ , is greater than the maximum amount of solute that is dissolvable in the solvent  $dis_{max}$  and is governed by equation 5.

$$F = (m_s + d_w \cdot (v_{robot} - (m_s - dis_{max})/d_s)) \cdot g \quad (5)$$

Where  $m_s$  is the mass of the solute in  $kg$ ,  $d_w$  is the density of the solvent in  $kg/cm^3$ ,  $v_{robot}$  is the volume of the robot in  $cm^3$ ,  $dis_{max}$  is the maximum amount of solute that can be dissolved in  $kg$ , which is based on the volume of the robot and the solute and solvent themselves,  $d_s$  is the density of the solute in  $kg/cm^3$  and  $g$  is the gravitational acceleration in  $m/s^2$ .

### 3.1 Sodium Chloride Example

By taking sodium chloride as the solute and distilled water as the solvent, it can be determined through experimentation that  $35.7g$  of sodium chloride can be dissolved in  $100cm^3$  of water at  $20^\circ C$  or room temperature [6].

Then, by applying Eq. 4 and Eq. 5 for sodium chloride and distilled water, the theoretical downwards acting force, produced by a robot, which is using this fluid to change its buoyancy can be determined. Fig. 5 shows how this theoretical force produced by the solution increases with sodium chloride concentration for a  $100cm^3$  robot. An interesting observation from Fig. 5 is that the maximum dissolvable quantity of sodium chloride in phase 1, produces a greater force than the minimum undissolvable quantity of sodium chloride in phase 2. This occurs due to the reduction in distilled water at the start having a greater effect on the force than the increase in sodium chloride.

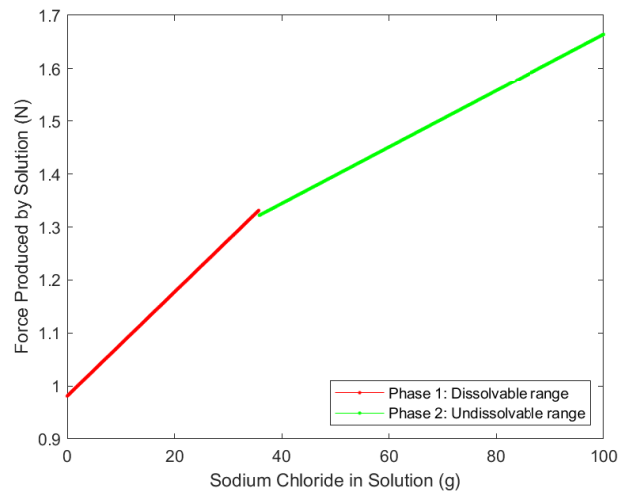
## 4 Case Study: Two Link Robotic Arm

We built a two link robotic arm as seen in Fig. 6 and Fig. 7 to examine the affect of our buoyancy based actuation method. Each link could be inflated with the fluids to enable it to move up and down independently of the other link.

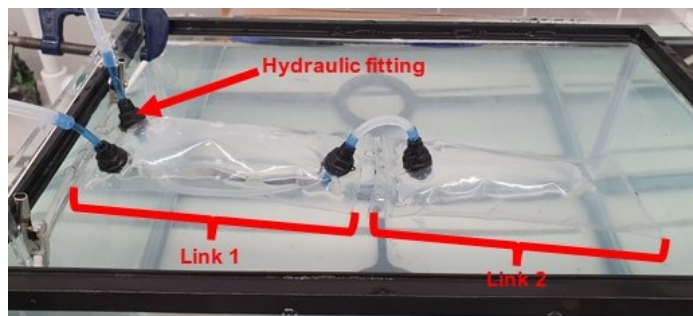
### 4.1 Design and Build

The links were heat welded from thin low density polyethylene (LDPE) sheets using a plastic bag sealer. Small holes in the links were made for the hydraulic connectors from which hydraulic tubes could be connected to, as shown in Fig.

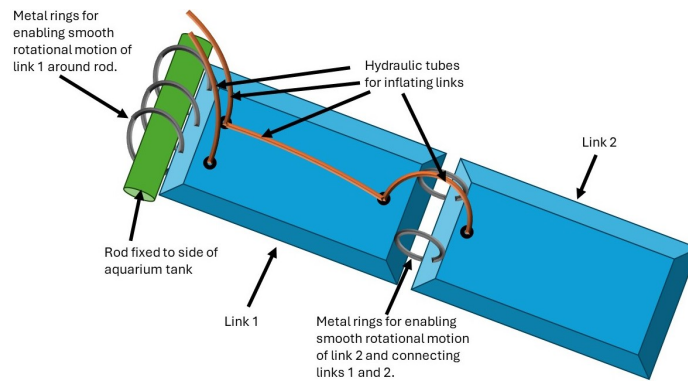




**Fig. 5.** Shows the theoretical force increase as the concentration of sodium chloride in a solution increases, inside a robot, with a volume of  $100\text{ cm}^3$  at  $20^\circ\text{C}$ .



**Fig. 6.** Shows the robot with two links.



**Fig. 7.** 3D rendering of two link soft robot arm

6. The hydraulic connectors were then screwed into the links to make water tight seals. Thin, silicone hydraulic tubes provided the means for transporting water to the links without compromising the robots ability to change bending angle. A bypass hydraulic tube to supply water to link 2 was placed through link 1, to prevent tension being placed on the links, which would prevent them from bending. Flexible metal rings were created from the rings of a spring to enable the links to be connected together and link 2 to rotate around link 1 and to connect link 1 to the rod, which enables link 1 to rotate around the rod.

## 5 Results

### 5.1 Experimental Setup


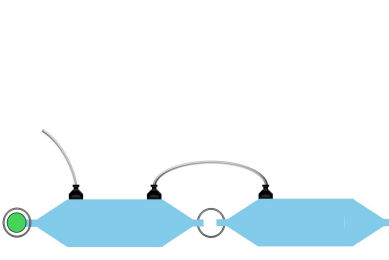

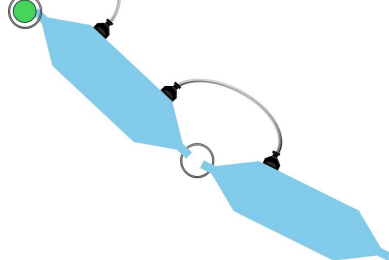

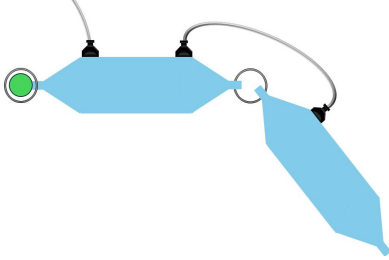

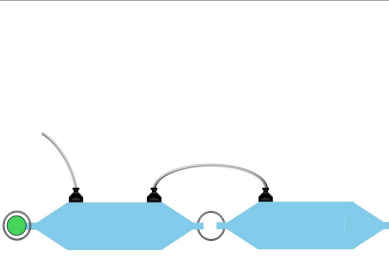
An aquarium tank was filled with distilled water with a negligible amount of sodium chloride. Sodium chloride was chosen as the solute and distilled water was chosen as the solvent in the solution that was pumped into the robot links. The salt solution used to inflate the robot consisted of approximately 36 grams of sodium chloride for 200 ml of distilled water. The robot was anchored to a piece of acrylic, using the rod, close to the surface of the water. A syringe was used to pump different premixed fluid solution into and out of the robot.

### 5.2 Robot Link Positions

The robot started in the configuration shown in Tab. 2 (a), where it was parallel and in line with the surface of the water. The salt solution was then added to link 1, as shown in Tab. 2 (b) causing the robot to orientate link 1 downwards and as link 2 was attached to link 1, it was also oriented downwards. The premixed salt solution was then removed from link 1 and placed in link 2 causing link 2 to be orientated downwards while link 1 remained at the surface of the water, as shown in Tab. 2 (c). The final test determined whether the robot was able to achieve neutral buoyancy by filling both links with distilled water. The results of which are shown in Tab. 2 (d), where the robot appears to show itself in a neutrally buoyant position. A limitation of this test is that the robot was anchored close to the surface of the water, so it is difficult to distinguish whether the robot was experiencing neutral buoyancy or positive buoyancy. Further tests are required to determine whether the robot was experiencing positive buoyancy or neutral buoyancy. These further tests would require the robot to be anchored at a greater water depth, such that the anchoring point is submerged further underwater.

## 6 Conclusions and Future Work

This paper proved both mathematically and experimentally that buoyancy actuation can be achieved in a soft robotic system, through the inflation of the robot with different density fluid solutions to the fluid solution the robot is immersed in, which enables the robot to generate a specific amount of force.

Movement	Experimental Image	Drawing of Movement
(a)		
(b)		
(c)		
(d)		

**Table 2.** Robot demonstrating different configurations with different solutions. (a) shows robot in initial configuration without any solution inside the links. (b) shows salt solution inside link 1. (c) shows salt solution inside link 2. (d) shows distilled water in links 1 and 2 demonstrating neutral buoyancy.

There persists many challenges that need addressing to make a robot powered by this buoyancy system useful. This includes the prevention of air from going into the robot causing it to become positively buoyant to the extent that the addition of a denser fluid would not be able to counteract the upward buoyant force. Additionally, a suitable robot design is needed that has separate chambers, in which the negatively buoyant, denser solutions can be pumped in without contaminating the positively buoyant, less dense solutions through the remainder of remnants of solute after repeated actuation. Furthermore, a suitable control system is needed to pump different density fluid solutions into and out of the robot for precise position control as this paper only considers constant force values and not the position of the robot underwater. This control system could make use of peristaltic pumps to pump fluid solutions into and out of the robot. One could also consider a reinforcement learning approach with sensors that can detect depth as the control system would need to be highly adaptable due to the high dynamic variability of the underwater environment.

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