# Residual Stress-Based Soft Robot with Capability for Grasping and Buoyancy Control

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## Supplementary information

Video A. Soft robot that moves up and down underwater

Video B. Soft robot that lifts and puts down the screw

Video C. An amphibious soft robot that moves between water and the floor

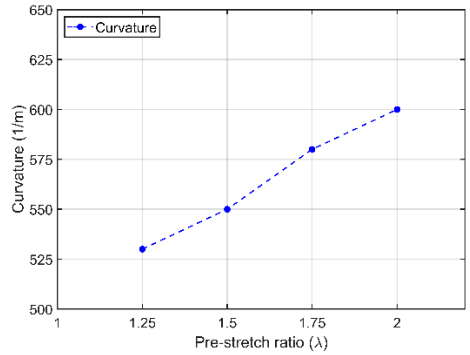



Figure S1. Curvature of the soft robot as a function of pre-stretch extension.

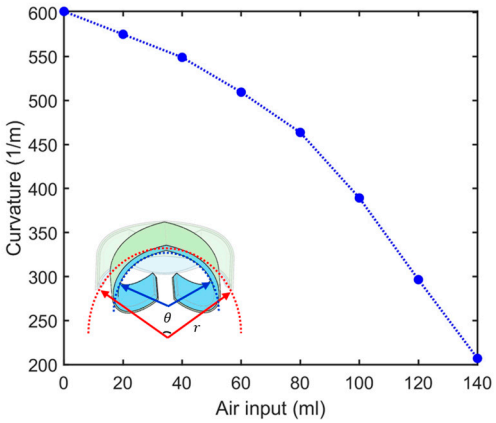



Figure S2. The radius of curvature decreases with air input.

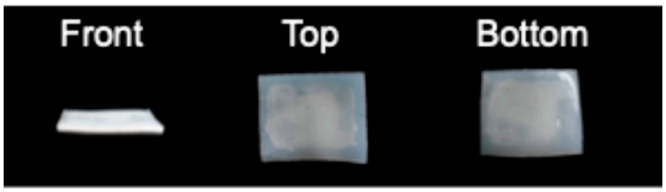



Figure S3. Fabricated specimen without pre-stretch.

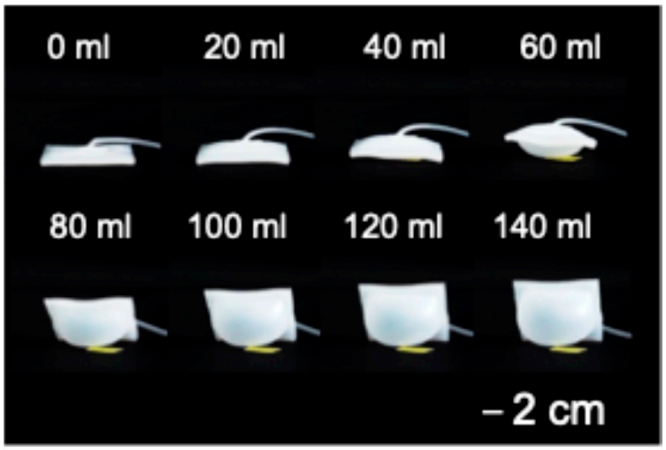



Figure S4. Specimen from S2 with air injection.

Figure S5. The resistance values from the integrated flex sensor demonstrate consistent performance over 16 (top) and 57 (bottom) operational cycles. Raw sensor data were processed with drift compensation to account for the inherent characteristics of the flex sensor.

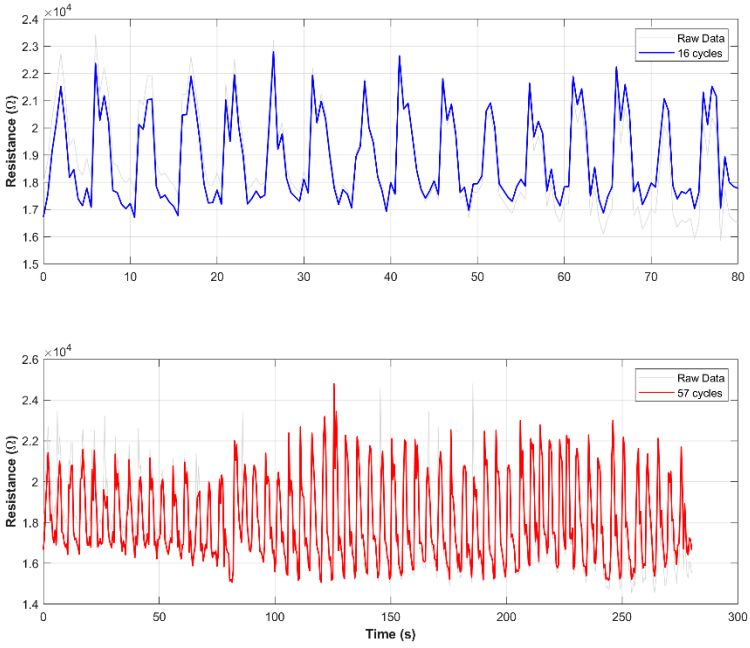


**Table S1.** Performance comparison between the proposed soft robot and existing underwater soft robot

| Comparison Criteria | Proposed soft robot | Wu et al. | Sinatra et al. |
|---|---|---|---|
| Actuation Mechanism | Bending driven by residual stress between two polymer layers | Pump driven soft suction disk actuated by 3D-printed linkages and tubular bellows | Nanofiber reinforced silicone matrix driven by hydraulic pressure |
| Hardware Complexity | Low. Fabricated simply by stretching a soft polymer and curing a stiffer polymer on top | High. Requires modular mold casting, a complex 3D-printed linkage mechanism | Moderate. Requires nanofiber spinning, sequential co bonding of silicone layers and attachment to a 3d printed palm hub |
| Manipulation | Capable of lifting various objects, including screw and safe due to soft materials but relies on elastic restoring stress which lacks fine tuned low pressure control for extreme fragility | Capable of nondestructive capture of fish and turtles, but specifically engineered to stay below 1kPa of contact pressure | Specifically design for gelatinous marine organisms, maintaining an ultra-low contact pressure of ~0.0455 kPa |
| Material | Silicone polymer Ecoflex 30 Dragon skin 30 | Silicone (suction disc), TPU (tubular bellows), photosensitive resin (3D printed parts) | Silicone (Dragon Skin 20), polymer nanofibers (Nylon-6 polyurethane), and photopolymer (3D printed palm) |
| Presence of rigid components | None. | Yes. 3D printed linkage mechanisms, a slider rod, and rigid stents inside the suction cups | Yes. 3D printed central hub (palm), stainless steel fasteners |

Section S1. Energy consumption analysis

To evaluate the practical application of the soft robot, the energy consumption required for a buoyancy control cycle was estimated. The mechanical work required to expand the internal air chamber is defined by the integral of the net pressure over the volume change.

The work required to expand the internal air layer is

$$\boldsymbol{W} = \int_{\boldsymbol{V_i}}^{\boldsymbol{V_f}} \boldsymbol{P_{net}}(\boldsymbol{v})\boldsymbol{dV}$$

where $\boldsymbol{P_{net}}(\boldsymbol{v})$ is the internal pressure required to overcome both the hydrostatic pressure and elastic restoring force of the bilayer membrane. $\boldsymbol{V_i}$ and $\boldsymbol{V_f}$ are the initial and final volumes, respectively.

For a maximum inflation of 140 mL at an average pressure of 3 kPa and a depth of 21 cm, the total energy consumed per cycle is approximately 0.43 J. This low energy requirement suggests that the robot can operate for extended periods using small-scale portable power sources. For instance, a compact 1.85 Wh battery could theoretically support over 15,000 inflation/deflation cycles, making it suitable for persistent environmental monitoring and search-and-rescue missions in confined aquatic spaces.