



Bio-Inspired Pneumatic Soft Actuators for Underwater Robots Sea Life Exploration and Conservation

A Thesis submitted for the degree of Master of Science in MSc Mechanical Engineering

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Abstract- Coral reefs represent some of the most diverse and threatened ecosystems on the planet, making their ongoing monitoring, exploration, and conservation a global imperative. Traditional observation methodologies, highly dependent on human divers, are constrained by limited reach, high operational risks, and the potential for habitat disturbance. In recent years, underwater robotics has revolutionized marine exploration; however, most conventional robots—characterized by rigid structures and traditional actuation—lack the compliance and adaptability needed for delicate interactions within reef environments. Inspired by the exceptional flexibility and dexterity of marine animal, this research presents the development of a bio-inspired underwater robot utilizing advanced pneumatic soft actuators. These actuators allow for sophisticated, flexible motion patterns—enabling swimming, crawling, grasping, and gentle manipulation. The robot is designed to minimize impact on benthic habitats while providing access to complex and sensitive reef structures, facilitating high-resolution monitoring, environmental data collection, and potential intervention or restoration activities. Through computational simulation and application scenarios, the results of this project aim to contribute to advancements in marine robotics, offering potential applications in environmental monitoring, marine research, and sustainable underwater operations. This work advances the field of marine robotics and provides a robust technological foundation for future coral reef observation, conservation, and broader oceanographic exploration efforts.

Keyword- Bio-inspired underwater soft robotics, Pneumatic actuators, marine conservation, ocean exploration; environmental sensing.

1. INTRODUCTIONS

Coral reefs are recognized as some of the most diverse and valuable marine ecosystems, supporting high biodiversity and providing critical ecosystem services such as fisheries, coastal protection, and tourism. However, they are facing unprecedented threats from climate change, pollution, and overfishing, making their monitoring and conservation an urgent global priority [1]. Traditional approaches to coral reef observation—primarily based on diver surveys and manual sampling—suffer from significant constraints, including limited spatial and temporal coverage, diver safety risks, high operational costs, and the potential for physical disturbance of fragile reef habitats. As a result, there is a growing need for advanced and minimally invasive technologies that can provide continuous, accurate, and extensive data on reef health and ecosystem dynamics. The development of robotics in the world technology has been spreading and massively garnered attention with their potential application in almost every environment. Although ingenious, such

invention is still yet widely improved in underwater exploration, environmental monitoring, and marine operations. These robots have provided numerous assistances over the years by studying and interacting with aquatic environments in a manner that minimizes ecological disruption. Robotics, particularly underwater robots, have emerged as transformative tools for environmental monitoring and underwater exploration. Robots such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) allow researchers to collect data over much wider areas and for much longer durations than is possible with human divers and can access hazardous or deep environments beyond safe human reach [2]. Importantly, these robots can also be equipped with a wide range of sensors, providing high-resolution visual, acoustic, and environmental measurements.

Recently, soft robotics has gained increasing attention in underwater research due to its intrinsic compliance, high adaptability, and environmentally friendly interaction capabilities.

Inspired by the unique biomechanics of marine animals such as octopuses and other cephalopods, soft robots constructed from flexible and deformable materials can safely adapt to complex substrates and interact with delicate marine life, minimizing ecological disturbance [1]. As noted by Cardenas et al. (2023), “Bio-inspired soft robots are uniquely suited for navigating the unstructured, delicate, and dynamic terrain of coral reefs.” The octopus, with its extraordinary flexibility and motor dexterity, has become a key model in the design of bio-inspired soft robotic manipulators capable of grasping, crawling, and compliant locomotion. Pneumatic actuation, which enables soft robots to bend, elongate, and twist via the controlled pressurization of internal chambers, provides a promising solution for achieving such biomimetic movements underwater. Robots employing pneumatic soft actuators have demonstrated the ability to perform complex tasks, including multi-arm swimming and object grasping, as well as bipedal walking and three-dimensional spatial movements crucial for coral monitoring and restoration [4]. By leveraging bio-inspired designs and pneumatic actuation, underwater soft robots can achieve both efficient swimming and gentle manipulation or observation at the reef interface. Such platforms are well-suited for the challenges of coral reef monitoring and conservation, making it possible to collect valuable data in a non-intrusive way, and to support advanced applications such as restoration, sampling, and long-term ecological studies.

The implications of this study extend beyond technical advancements. Swimming robots inspired by the bio-anatomy of a manta ray have the potential to revolutionize underwater exploration, enabling researchers to access previously unreachable depths and collect data on fragile ecosystems with minimal disruption. Such robots could play a critical role in environmental monitoring, helping to track pollution levels, study marine biodiversity, and assess the health of coral reefs. Their adaptability and precision also make them valuable tools for search-and-rescue missions, underwater construction, and other industrial applications. This research aligns with the growing demand for sustainable technologies that harmonize with natural systems rather than exploit them. By drawing inspiration from the natural bio-aquatic

creature and utilizing advanced materials and actuators, this project contributes to the vision of creating robotics that coexist with and benefit marine environments. The combination of bio-inspired design and cutting-edge technology offers a glimpse into the future of underwater robotics, where efficiency, adaptability, and environmental compatibility are at the forefront. This research aims to develop a bio-inspired underwater robot using pneumatic actuators that can effectively and safely support sea exploration, coral reef observation, and conservation tasks. By integrating insights from natural systems and advances in soft robotics, the proposed robot aspires

2. LITERATURE REVIEW

2.1 Advanced Actuation Mechanisms Using Soft Pneumatic Actuators

Traditional actuation systems in underwater robotics often rely on rigid, bulky, or inefficient mechanisms that do not adequately mimic the flexible, compliant movements of biological organisms. Soft robotics, which are inherently safe and adapt well to unstructured environments due to their softness, are expected to satisfy the needs of robots that interact safely with humans.[3]. The actuators utilize pressurized fluids or gases (usually water or air) to induce controlled deformation in elastomeric materials, producing motions analogous to biological systems. Recent designs of octopus-inspired arms and tentacles feature multiple chambers or segments, each capable of independent bending, elongation, or twisting, resulting in highly dexterous manipulators. Innovation in materials—with low hardness silicones and

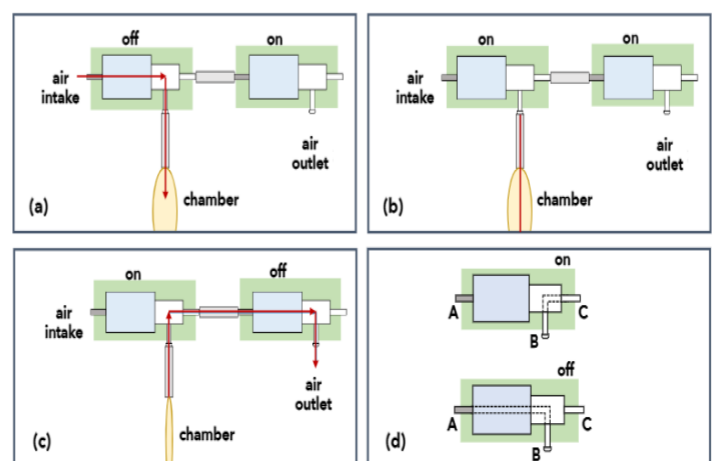


Figure 1. Activation scheme for controlling air flow to the pneumatic chambers, for (a) inflating the chamber, (b) maintaining pressurized air in the chamber, and (c) deflating the chamber. (d) Three-port solenoid valve operation [3]

flexible composites—enables actuators to achieve lifelike motion and enhanced safety during environmental interactions.

In the context of soft pneumatic actuators application on underwater robotics, its strength is in it prioritize precise, rapid, and energy-efficient actuation, which is optimal for many underwater applications where compliance and safety are key considerations. In contrast, it also has inherent challenges, such as potential leakage and the requirement for robust, waterproof control components, yet these issues are generally outweighed by their advantages in terms of control, modularity, and operational simplicity. This ensures both the flexibility needed for biomimetic motion and the rigidity required for efficient thrust generation, closely mirroring the motion profiles of marine animals like the manta ray. Simultaneously, miniaturisation strategies such as advanced microfabrication and embedded pneumatic networks are employed to reduce system volume and integrate air channels, sensors, and control circuitry directly into the robot's body. This approach not only improves energy efficiency by minimizing dead volume and pressure loss, but also allows for more compact, seamless integration—critical for agile and efficient underwater propulsion systems. these innovations support the development of a robust, lightweight, and biologically inspired actuator platform capable of lifelike, responsive motion in aquatic environments.

2.2 Improved Hydrodynamic Efficiency Through Bio-Inspired Design

A critical requirement for underwater robots is their ability to move efficiently through water with minimal energy loss and maximum manoeuvrability. Hydrodynamics plays a pivotal role here, as the shape and form of a robot determine the flow patterns around it, the generation of lift and thrust, and the overall drag encountered during motion. Conventional robots often fall short in this area, as their housings and propulsion mechanisms do not effectively manage fluid flow. The main issues including its sub-optimal shape and flow separation which have rigid, boxy designs create turbulent wakes and flow separation, thus increase drag and dissipate the mechanical energy intended for propulsion. The essence of soft robotics lies in mimicking the compliance, adaptability, and actuation strategies observed in marine organisms such as octopuses, squids, and rays. These animals demonstrate extraordinary locomotion and manipulation capabilities through flexible, muscular-hydrostat structures—devoid of rigid skeletons—allowing them to squeeze through narrow crevices, grasp irregular objects, and move efficiently within dynamic environments.

There is also problem with existing moving systems attempt to mimic biological counterparts but fail to capture the continuous, smooth movement and the dynamic fluid-structure

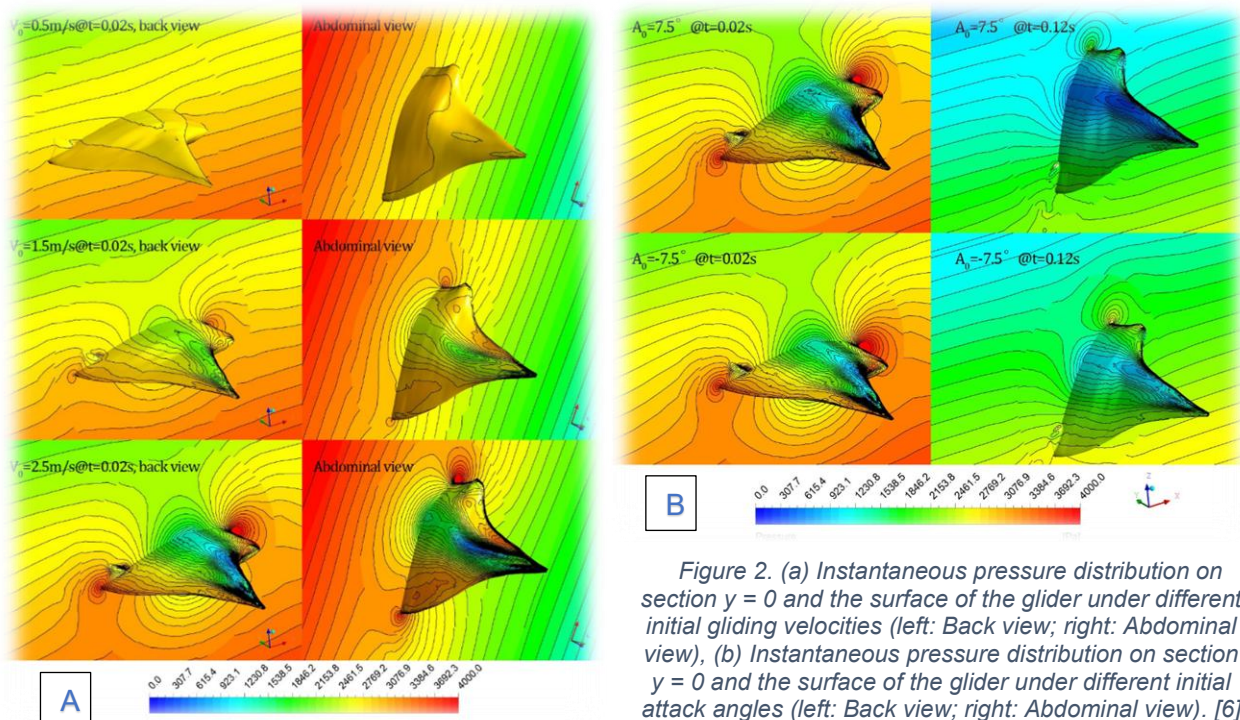


Figure 2. (a) Instantaneous pressure distribution on section $y = 0$ and the surface of the glider under different initial gliding velocities (left: Back view; right: Abdominal view), (b) Instantaneous pressure distribution on section $y = 0$ and the surface of the glider under different initial attack angles (left: Back view; right: Abdominal view). [6]

interaction observed in high-performance swimmers like manta rays. This causes the interplay between the robot's structure, and the surrounding fluid often does not adapt to varying speeds or environmental conditions, leading to inefficient energy usage during acceleration, deceleration, or manoeuvring.

2.3 Technology Applications in Coral Reef Monitoring and Marine Conservation

Robotics has recently expanded the toolkit available for reef scientists, with applications ranging from environmental surveillance and health assessments to the deployment of coral restoration technologies. Remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and hybrid underwater vehicles (HUVs) have been deployed to replace or supplement diving-based studies, particularly in complex or hazardous environments [1]. ROVs provide continuous video and sensor data in shallow as well as deeper waters, while AUVs allow for fully autonomous data collection, often incorporating sonar, cameras, and chemical sensors to map benthic environments. Hybrid vehicles combine the advantages of both tethered and autonomous modalities, reducing risks of data loss and increasing mission durations. These robotic systems not only extend the reach of monitoring into deeper or logistically challenging areas but also minimize human risk. Beyond single-vehicle deployments, cooperative and swarm robotics represent emerging trends in underwater monitoring. Inspired by fish schools

and insect colonies, robotic swarms are being tested for coordinated imaging, mapping, and environmental sensing. Their decentralization increases resilience and scalability, although challenges remain in underwater communication and coordination [1]. Operating in the corrosive and pressure-variable conditions of underwater environments places immense strain on robotic structures—especially those utilizing soft, flexible components.

Conservation monitoring must minimize anthropogenic disturbance. Traditional propulsion systems, like thrusters, can stir sediments, disturb benthic organisms, or generate noise that affects fish behaviour. Soft, bioinspired robots that emulate the silent undulatory propulsion of fish or jellyfish reduce acoustic disturbance and mechanical interference, ensuring that data collected reflect natural ecosystem behaviour without human-induced bias. This emphasis on reducing observer bias and physical risks associated with diver-based surveys. Bioinspired soft robots excel in constrained and heterogeneous environments. For example, octopus-inspired manipulators can gently grip or interact with substrates, making them ideal for sampling, coral out planting, or deploying sensors in coral nurseries — areas that the review identifies as underexplored opportunities for robotics. Their compliance allows them to operate close to reefs with reduced collision risk, accessing microhabitats that rigid robots cannot.

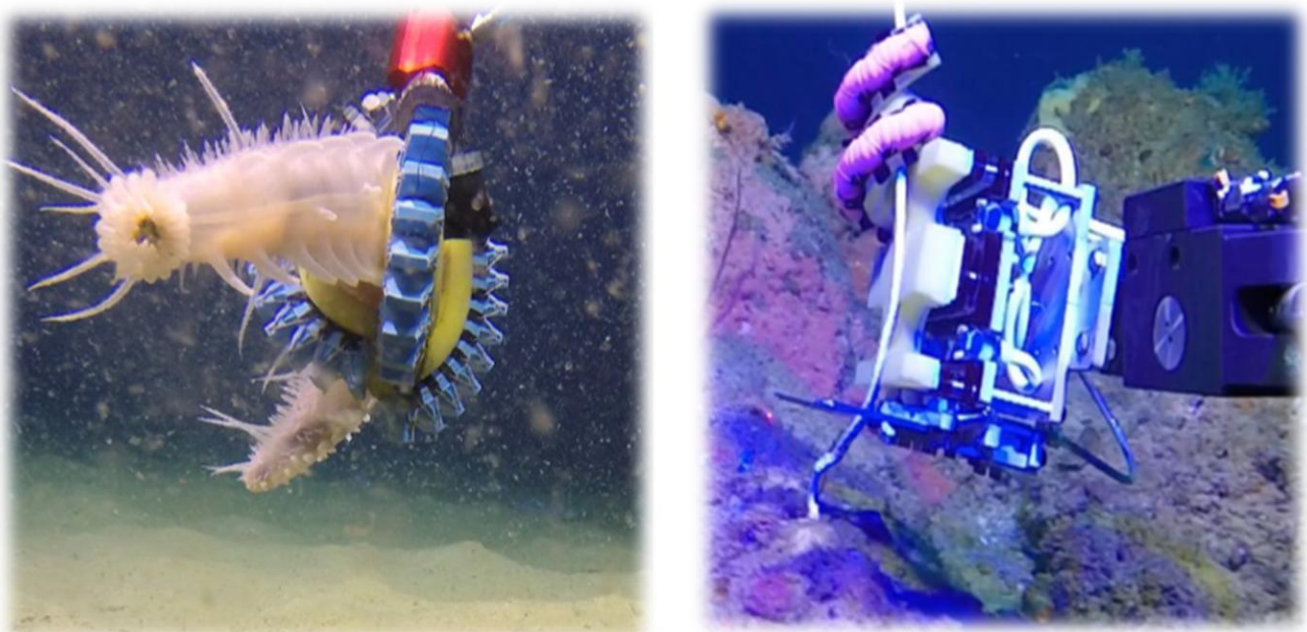


Figure 3. Example of soft gripper for deep-sea biological conservation. (a) Three finger gripper with bellows-type actuators, grasping a holothurian at 1800 m in the Channel, and (b) “Boa” style fiber-reinforced actuator grasping a whip coral, [27]

3. OBJECTIVES AND METHODOLOGY

3.1 Objectives

The aim of the study is to build a bio-inspired design underwater robotic with pneumatic design. This is done in effort to improve the advancement of underwater robotics such as material testing, improving design shape, practicality of pneumatic actuators and effectiveness in underwater, ideally sea faring, exploration and preservation application.

Key Research aims:

(1) Optimizing Design Performance: This objective focuses on refining the bio-inspired geometry and actuation mechanism to enhance underwater locomotion efficiency. Drawing inspiration from several sea creatures' behaviour and physical aspects, the design will incorporate modular pneumatic chambers to achieve adaptive stiffness and fluid-structure synergy. Optimization efforts will target improved thrust generation, manoeuvrability, and energy efficiency under varying flow conditions.

(2) Developing a Precise 3D Model: A high-fidelity 3D model of the robotic system will be constructed using advanced CAD tools. The model will include detailed representations of the bellows structure, internal pneumatic channels, and flexible limb assemblies. This digital prototype will serve as the foundation for simulation workflows, enabling accurate analysis of deformation, flow interaction, and actuator response.

(3) Conducting Detailed Simulation Evaluations: Using Finite Element Analysis (FEA), the study will perform comprehensive simulations to evaluate structural integrity, hydrodynamic performance, and material behaviour. The simulations will assess pressure-volume dynamics, flow-induced deformation, and actuator efficiency across a range of operating scenarios. These evaluations will inform design iterations and validate theoretical models.

(4) Practical Prototype Evaluation and Testing: A physical prototype will be fabricated to validate simulation results and assess real-world performance. Experimental testing will include buoyancy control trials, limb actuation response, and underwater manoeuvrability assessments. Sensor integration (pressure and attitude) will

provide feedback for closed-loop control, enabling refinement of the pneumatic system and confirming the viability of the bio-inspired approach.

3.2 Methodology

3.2.1 Design Model Development

The underwater robots developed in this study specifically tailored and designed to be like commercially available ROVs but with slightly smaller dimensions to account in energy saving and material and practicality efficiency. The key parameters for each part will be specified in tables next to the design figures. The model development first started in the moving/manipulation aspect, thus progress in two design inspiration taken from ocean bio-organism. The first design is inspired from the flexible and gliding movement of manta-ray:

From a hydrodynamic standpoint, manta-inspired fin designs offer superior manoeuvrability and exploit leading-edge vortex dynamics to maintain stable flow and enable agile turning, tilting and floating efficiently. Using NACA 0015-like profiles shows manta fins produce characteristics not only reduce energy consumption but also extend operational endurance, making them ideal for long-duration missions. Additionally, the biomimetic elegance of manta ray locomotion lends itself to scalable, modular designs that can be adapted for various sizes and functionalities, from compact inspection bots to larger autonomous platforms.

Table 1.. Manta Ray Inspired Limb Parameters

Dimension	Value (mm)
NACA Profile	2221
Wing Chord Ratio	4:2:1
Chord Length	78
Wingspan Length	143
Wingtip Length	14
Overall Wing Width	88
Wingspan Back Gaps	2.9
Wingspan Chambers Width	5
Wingspan Chamber Length	5, 7,8,11,14,16, 23
Wingspan Chamber Volume	0.0112 L

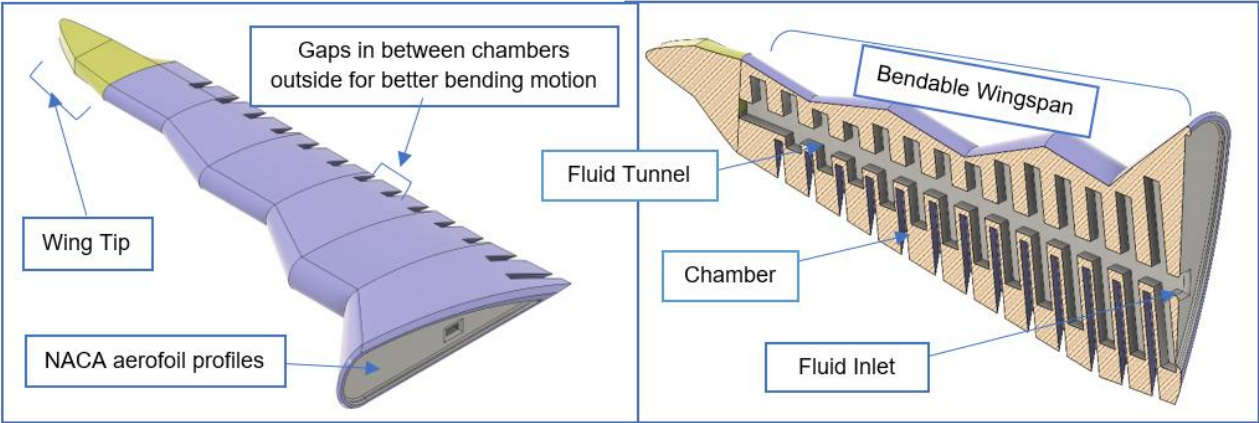


Figure 4. Manta Ray Inspired Limb Design

Table 2. Trilobites Imagined Limb Design Parameters

Dimension	Value (mm)
Limb Length	120
Limb Wide	35
Limb Thickness	5
Limb Chamber Wide	20
Limb Chamber Length	15
Limb Volume	0.00698 L
Fluid Inlet Diameter	3

For the next approach, implementing trilobite-inspired limb structures in the design of ROVs and soft robotics systems offers a fascinating and functionally rich approach to underwater locomotion, particularly in environments where stability, energy efficiency, and terrain adaptability are critical. Trilobites, as ancient marine arthropods, evolved a diverse array of limb morphologies that enabled them to thrive across benthic and pelagic zones for hundreds of millions of years. Their segmented, multi-jointed appendages were not only effective for crawling and burrowing but also contributed to hydrodynamic lift and stability during movement across the seafloor. Recent biomechanical studies suggest that certain trilobite features—such as genal prolongations and trident-like projections—may have played a role in generating negative lift, allowing these organisms to resist overturning in turbulent flows and maintain position with minimal energy expenditure. By emulating these limb dynamics in robotic systems, engineers can design underwater platforms that exploit passive hydrodynamic forces to enhance stability and reduce the need for constant active control. For example, soft robotic limbs modelled after trilobite appendages could be actuated pneumatically to mimic the rhythmic gait of benthic locomotion,

enabling the robot to traverse uneven substrates while maintaining low drag profiles. The initial design process focused on this 3D model to achieve an accurate and precise computation and highlight the impact of the actuators cross-sectional geometry on its performance.

The design will be actuated by mechanism that utilizes a bellows chamber as a compact and

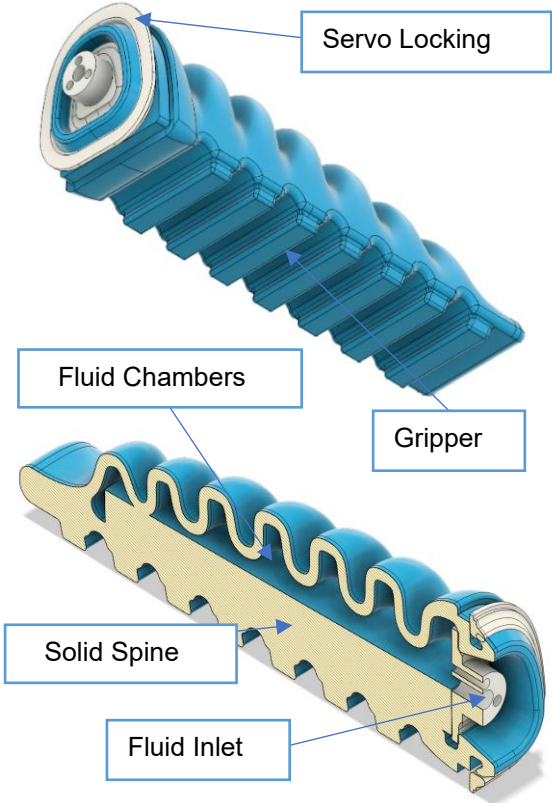


Figure 5. Trilobites Interpreted Limb Design

efficient fluid displacement mechanism to power a soft actuator. When the bellows is compressed, mechanically through servo motor and pneumatically forces fluid (for this study we use water for much larger pressure) through a

connected outlet tube into the soft actuator. The actuator, made from a flexible elastomer, is designed with internal asymmetries or fibre reinforcements that cause it to bend in a controlled direction as it fills. This bending motion is driven by the hydraulic pressure generated by the bellows, allowing for smooth, adaptive movement ideal for underwater environments. The system can be enhanced with valves to regulate flow and prevent backwash, and sensors can be integrated to monitor pressure or deformation for closed-loop control. Overall, it's a simple yet elegant way to convert mechanical input into fluidic actuation, enabling precise and biomimetic motion in soft robotic systems.

Table 3. Bellow Parameter

Dimension	Value (mm)
Bellow Length	40
Bellow Inner Diameter	35
Bellow Outer Diameter	25
Bellow Volume	~0.00019 L
Fluid Outlet Diameter	2

3.2.2 Governing Equations

The kinematics of soft actuator for the movement limbs are modelled using the constant curvature assumption, a widely accepted method in continuum robotics. This method simplifies the actuator as a shape that can be described by a circular arc of fixed curvature when subject to actuation. The constant curvature framework allows the mapping of actuation inputs—specifically, the lengths (or contractions) of the

chambers—into a unique configuration of the actuator, defined by a curvature radius, a bending plane angle, and a curvature angle. This modelling approach is particularly suitable for soft robots, where traditional rigid-link kinematics are inadequate due to the continuum and highly deformable nature of the structure. The relationship to determine the volume change ratio (α) from pressure (P) is given by:

$$\left[\alpha = \frac{V_c}{V_c^0} = \frac{PV_c^0 + P\Delta V_{sy} - (P - \bar{P})(V_{sy}^0 + V_t)}{PV_c^0} \right] \quad (1)$$

Where the variables are defined as:

(α): The volume expansion ratio of the actuator's chamber.

(V_c): The current volume of the deformed chamber after inflation.

(V_c^0): The initial (rest) volume of the chamber.

($\bar{P}$): The standard atmospheric pressure (e.g., 100 kPa).

(P): The measured inflation pressure in the chamber.

(ΔV_{sy}): The change in the volume of air in the syringe pump.

(V_{sy}^0): The initial volume of the bellow.

(V_t): The volume of the connecting tube.

This equation allows for the conversion of pressure measurements into the volume change ratio (α), which can then be used in the geometric computing framework for forward and inverse kinematics. The values for V_c^0 , V_{sy}^0 , and V_t are obtained from the design specifications of the pneumatic system

Each soft actuator embedded in the walking arms has bellow pumping fluid into the chambers making the actuators bend to contact and relax. To mathematically express this process, the stretch ratio along the length of the chamber is determined by both the clamped angle at the boundary and the chamber's initial height. Specifically, as internal pressure increases in the limb supplied by the fluid in the bellows, the chamber walls bulge outward, and the amount of this bulging can be related to the radius of curvature of the membrane, which itself is a function of both the height of the chamber and the

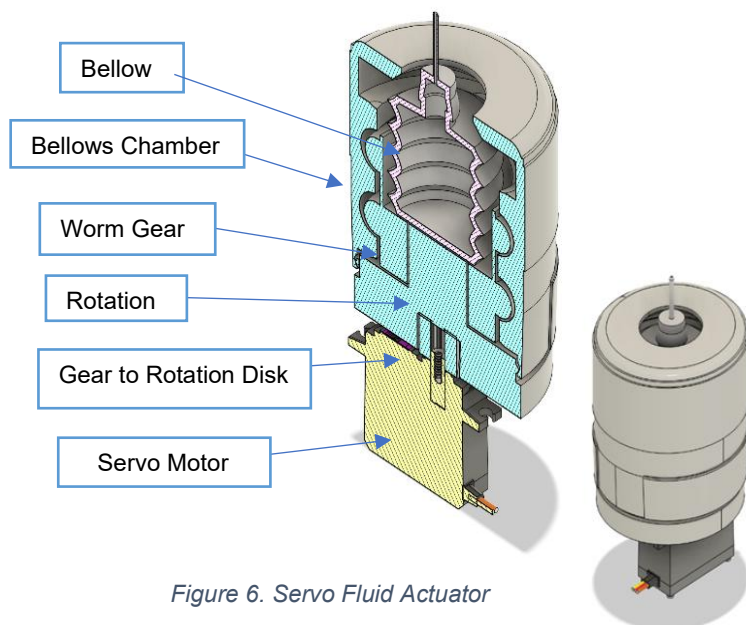


Figure 6. Servo Fluid Actuator

tilt angle. The greater the tilt, the more pronounced the bending for a given applied pressure, up to the limits imposed by geometry and material stretchability. The overall bending angle of the actuator is then computed by summing the contributions of each chamber segment, a process treated analytically using a piecewise constant curvature approach where each chamber arc is modelled as a section of a circle, and the aggregate arc length corresponds to the net bending observed.

To model pneumatic actuation in the Methods, discretize each inflatable chamber into internal tetrahedral actuation elements whose volumes are u_i so that the chamber total volume is

$$U = \sum_{i=1}^k u_i.$$

Enforce a prescribed global volume-expansion ratio α via the geometric constraint $fp(C) = \alpha U - \sum_{i=1}^k \alpha_i u_i \equiv 0$, where α_i are the per-element expansion ratios and C is the vector of actuation parameters. For each tetrahedral actuation element the target (actuated) geometry is obtained by isotropically scaling its rest shape about the element centroid by the factor $\alpha_i^{1/3}$ (i.e., a cube-root scaling), and then transforming that scaled shape into the element's current position and orientation to form the element's target configuration for the optimization iteration.

The local scaling factors $\{\alpha_i\}$ are selected proportionally to each element's instantaneous deformation relative to its rest shape and are solved together so that the set $\{\alpha_i\}$ satisfies the global constraint $fp(C)$ — in practice we compute

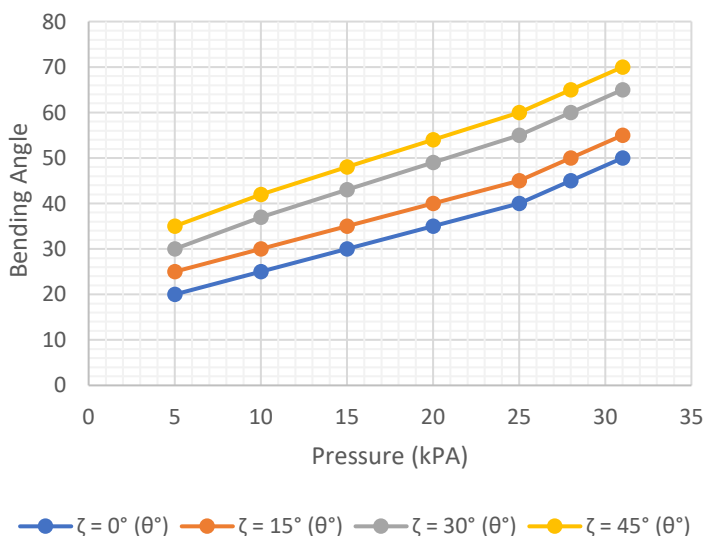


Figure 8. Simulated Pressure per Bending Angle of the Soft Limb

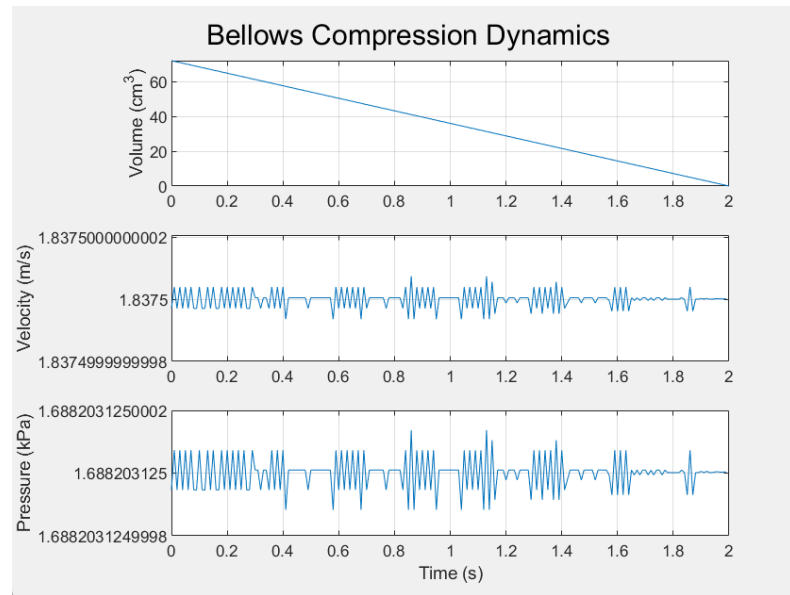


Figure 7. Bellow Compression Pressure Distribution over Time

$\{\alpha_i\}$ with a least-norm (minimum-norm) solver across the actuation elements to meet the global volume requirement while keeping the per-element changes minimal. These elementwise target shapes are integrated as high-priority actuation handles into the geometry-based elastic energy minimization (local-global iterative solver), so that in each iteration the actuation elements (given larger weights) drive the domain toward their targets while the global blending step enforces vertex compatibility across elements. Finally, map experimental inflation pressure to the model expansion ratio by calibrating $\alpha(P)$ in a closed test rig (e.g., measuring syringe displacement ΔV_{sy} and pressure P and applying the ideal-gas/volume balance to compute V_c and α), and use the calibrated $\alpha(P)$ curve as the model input so simulated chamber volume change reproduces measured PV behaviour.

Furthermore, as the pressure is progressively increased, another important phenomenon occurs at sufficiently high inflation, the lateral walls of adjacent chambers can come into contact, leading to squeezed regions and thereby further amplifying bending. This self-contact not only accentuates the curvature but also introduces additional nonlinearities, as the stiffness locally increases where walls press together; accurate prediction of this regime often requires numerical simulation, such as finite element analysis (FEA), to fully account for

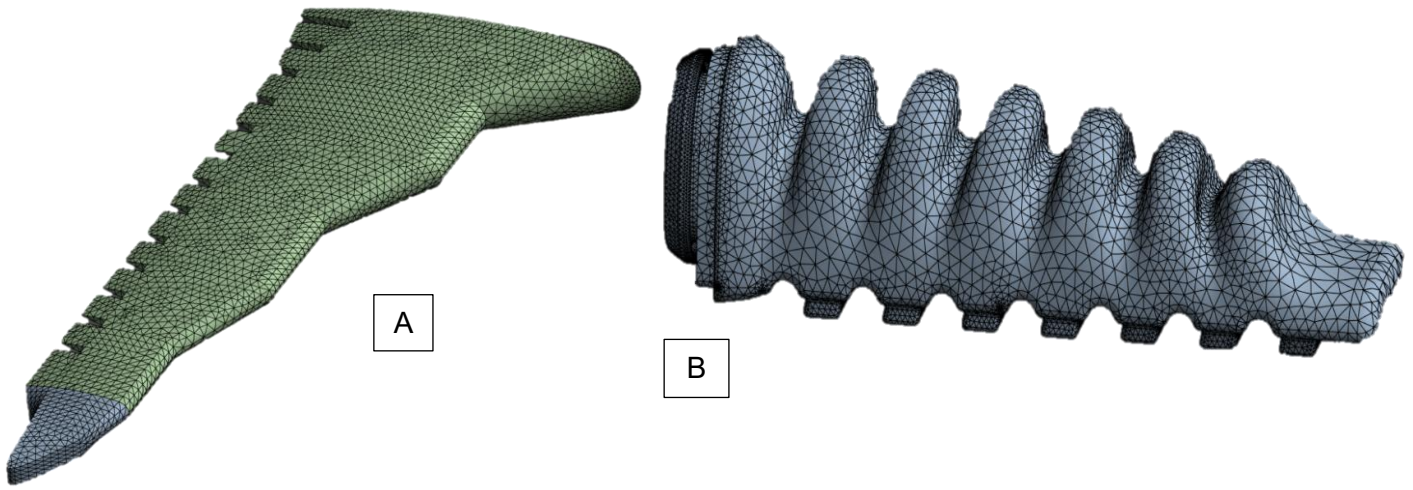


Figure 9. (a) Manta Ray Inspired Limb Meshed Model, (b) Trilobites Interpreted Limb Meshed Model

complex deformations, changes in wall contact area, and any local folding.

3.2.2.1 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) in the context of Static Structural simulation is a powerful computational method used to predict how physical structures respond to applied loads, constraints, and material properties under static conditions—that is, without considering time-dependent dynamics. It divides complex geometries into smaller, manageable elements and solves equations that describe stress, strain, and displacement across the structure. This approach is widely used in engineering to evaluate structural integrity, optimize designs, and understand deformation behaviour under various loading scenarios. In soft robotics, where

For this study, using Yeoh Hyperplastic Model which can be simulated through Finite Element Method (FEM) on ANSYS Structural. The strain energy function (W) for a 3-term Yeoh model is given by:

$$W = C_1(I_1 - 3) + C_2(I_1 - 3)^2 + C_3(I_1 - 3)^3$$

where (C_1, C_2, C_3) are material coefficients obtained from uniaxial tensile curve fitting, (I_1) is the first invariant of the deformation tensor. And for piecewise constant curvature (PCC), the principal stretches are defined as (λ_1): stretch in the length direction, (λ_2): width direction (often neglected, assumed ($\lambda_2 = 1$)), (λ_3): thickness direction (due to incompressibility, ($\lambda_3 = \lambda_1^{-1}$)).

Thus, $I_1 = \lambda_1^2 + \lambda_1^{-2} + 1$

materials are highly compliant and deformations are large and nonlinear, static structural FEA becomes especially valuable for simulating how soft actuators bend, stretch, or compress when pressurized or mechanically actuated. By assigning hyperplastic material models (such as Mooney-Rivlin or Ogden) and applying internal pressure loads or boundary displacements, engineers can visualize total deformation, stress distribution, and bending profiles with high fidelity. This enables precise tuning of actuator geometry and material composition to achieve desired motion characteristics, making FEA an indispensable tool in the design and validation of soft robotic systems.

and by differentiating the strain energy function (W) with respect to the principal stretch (λ):

$$\sigma = \frac{\partial W}{\partial \lambda} = 2(\lambda - \lambda^{-3}) \sum_{i=1}^3 (\lambda - \lambda^{-1})^{2i-2}$$

Using 2D membrane theory with clamped ends the applied internal pressure (P) acts orthogonally to the inner walls, generating force per unit area. The force causes the membrane to stretch and bend., the lateral walls are approximated as an initially flat membrane deforming to a circular arc upon inflation we can get the Bending Radius:

$$\rho = \frac{h_2}{2 \sin \theta_m \cos \zeta}$$

where (h_2): initial height of the chamber, (θ_m): clamped angle, (ζ): chamber tilt angle (positive for clockwise tilt) The stretch ratio along the

membrane (λ) connects geometric displacement and deformation:

$$\lambda = \frac{\theta_m \rho}{\frac{h_2}{2} \cos \zeta} = \theta_m \sin \theta_m$$

The maximum elongation of the wall segment is:

$$\delta_1 = \frac{h_2}{2 \cos \zeta} \tan(\theta_m)$$

Numerical Relation of Bending Angle The arc length of the inextensible bottom layer is related to chamber geometry:

$$\varphi R = n(d_2 + 2d_1) + (n + 1)d_3$$

where (φ): bending angle, (R): radius parameter, (n): number of cavities, (d_1, d_2, d_3): geometric dimensions. From:

$$\delta_p \approx \delta_s = \sqrt{\rho^2 - (h_2 - 2h_4 - (\rho - \delta_1))^2}$$

3.2.2.2 Materials

The robot body and components are fabricated from three primary materials: Ecoflex 00-30 silicone rubber, polylactic acid (PLA) filament, and acrylic (PMMA) sheet. Ecoflex 00-30 (platinum-cure, Shore 00–30) is selected for soft cast parts because of its low modulus, high elongation, and tear resistance, making it well suited for compliant limbs and bellows. Ecoflex is mixed 1:1 by weight, vacuum-degassed, and poured into 3-D-printed molds; molds are often oriented (e.g., $\sim 45^\circ$) during cure to avoid trapped air and promote uniform filling, with cure times on the order of several hours (typical pot life ≈ 30 min and full cure ≈ 4 h depending on formulation). Parts cast from the same silicone can be bonded by applying a thin layer of uncured A/B mixture at mating faces prior to the final cure [3].

PLA is used for rigid structural elements and molds when a fused-deposition alternative is appropriate, owing to its stiffness and ready printability; PLA is compatible with most desktop FDM printers and is an economical choice for jigs, supports, and non-loadbearing housings. In our lab we print PLA parts using standard FDM practice (nozzle ~ 190 – 220 °C, bed ~ 45 – 60 °C, layer height 0.1–0.2 mm, print speed 30–60 mm/s, filament diameter 1.75 mm), and we store filament dry to avoid hydrolytic degradation and

where (h_4): another height parameter of chamber, the overall *bending angle* (φ) of the actuator is a function of the total arc length generated by the inflation of each chamber segment:

$$\begin{aligned} \varphi(R + h_1 + h_4) \\ = n(d_2 + 2d_1) + (n + 1)d_3 \\ + 2(n - 1)\delta_p \end{aligned}$$

so, the bending angle is,

$$\varphi = \frac{2(n - 1)}{h_1 + h_4} \delta_p$$

All above geometric and material quantities can be expressed as a function of the applied pressure (P), chamber tilt angle (ζ), and design parameters. Through substitution using the Yeoh constitutive model and geometry, you numerically solve for (φ) (bending angle) as a function of (P) and (ζ) Generally, the relationship is nearly linear when pressure is within operational range:

print artifacts; 3-D-printed PLA molds and fixtures are commonly used for silicone casting workflows Use of resin-printed molds (SLA/DLP) is an alternative when higher surface fidelity is required, but PLA remains a viable, lower-cost option for many rigid components and mold forms

Acrylic (PMMA) sheet is used for transparent or stiff structural panels where optical access or dimensional stability is required; typical supplier values for PMMA are density ≈ 1.17 – 1.20 g·cm⁻³, tensile strength ≈ 50 – 80 MPa, and glass transition near 100–110 °C. PMMA parts are fabricated by laser cutting or CNC machining and bonded with solvent cement or acrylic adhesives; edge finishing and polishing are used when optical clarity is necessary.

For reproducibility, record full vendor identification (product name, supplier, catalogue/part/lot numbers), batch/delivery dates, and datasheets for each material lot used. Where possible, verify key material properties experimentally and report test methods and results: Shore hardness (ASTM D2240), tensile strength and elongation (ASTM D412 or ASTM D638, depending on specimen geometry), tear strength (ASTM D624), flexural properties (ASTM D790), and density (ASTM D792). For printed PLA parts, report the printer make/model, nozzle diameter, filament brand and lot, slicer version

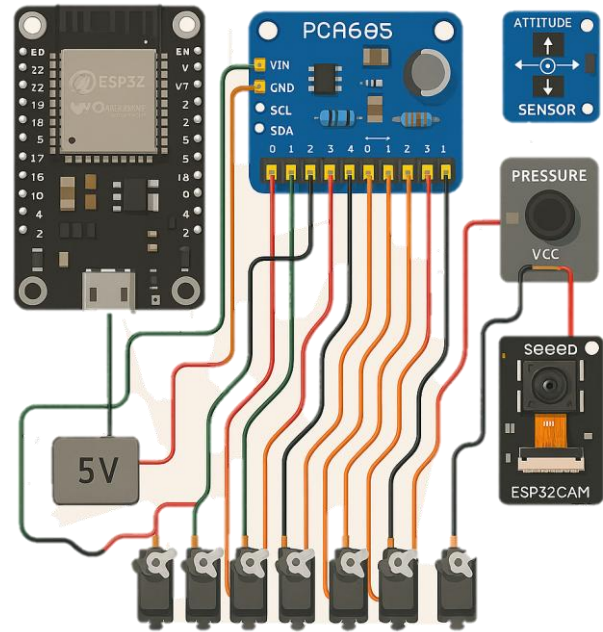
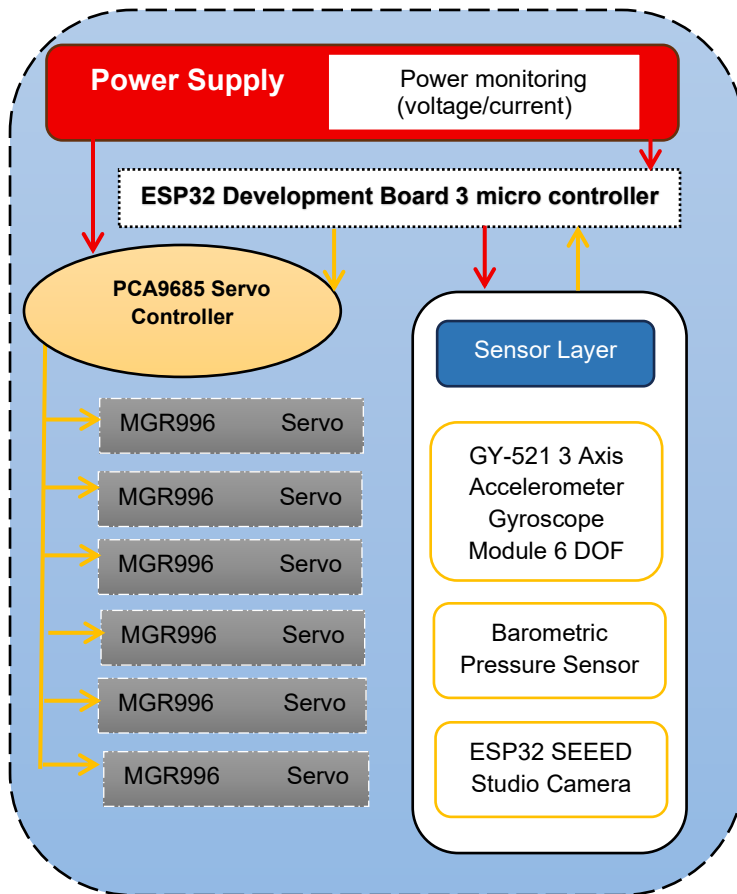


Figure 10. Structure of Control Schematics System.

and exact G-code or slicing profile, and post-processing steps (annealing, solvent smoothing, etc.). For silicone casting, document mixing ratios by mass, degassing procedure (vacuum level and time), mould orientation during cure, ambient and mould temperatures, pot life, cure time, and any applied surface treatments or bonding steps

3.2.2.3 Electronics

This electronic schematic in figure 8, underpins for a bio-inspired underwater robotic system, integrating actuation, sensing, and visual feedback through a modular and adaptive architecture. At its core, the ESP32 microcontroller orchestrates operations by interfacing with a PCA9685 PWM driver via I²C, enabling precise control of six servo motors responsible for fin articulation and buoyancy modulation. Environmental awareness is achieved through a pressure sensor that outputs analogue depth data and an attitude sensor—such as the MPU6050 or BNO055—that provides real-time orientation feedback. These inputs allow dynamic adjustment of motor behaviour based on hydrodynamic conditions. A dedicated ESP32-CAM module extends the system's

capabilities by capturing visual data for object detection or navigation, operating either independently or in coordination with the main controller. Power distribution is carefully managed: servos draw from a separate 5V source to prevent current overload, capacitors stabilize voltage fluctuations, and pull-up resistors ensure clean I²C communication. Together, these components form a responsive and environmentally adaptive control system, enabling complex underwater manoeuvres and real-time feedback integration essential for biomimetic propulsion and intelligent navigation

4. RESULTS AND DISCUSSION

4.1 3D Simulation Results of the Initial Models

Experimentally, these analytical and numerical predictions can be validated by systematically pressurizing physical samples of the actuators and tracking the bending angle and profile, often using image processing tools on photographs taken against a grid background. Observations generally confirm that positive tilts in the chamber walls—those that orient the tilt in the direction of desired bending—lead to significantly greater bending performance than negative tilts or untitled, rectangular chambers. Actuators incorporating a 30-degree positive tilt can exhibit up to 11–20% greater maximum deformation

compared to their non-tilted counterparts at the same pressure.

4.1.1 Deformation of the Model

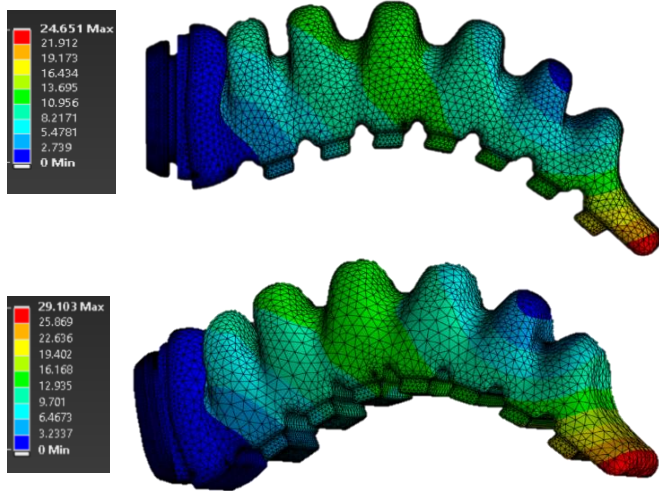


Figure 12. Total Deformation of Trilobites Imagined Design Limb

From a design perspective, this visualization underscores the importance of material selection and geometric tuning in soft robotics. The use of low-modulus elastomers like Eco flex 00-30 enables large, reversible deformations while maintaining structural integrity, and the simulation validates that the internal pressure can be effectively harnessed to produce controlled bending motions. This is particularly relevant for applications requiring delicate grasping or adaptive interaction with irregular objects, where rigid mechanisms would fail to conform or distribute force evenly.

The comparative bar chart illustrates the influence of pressure and angular parameter ζ on the maximum deformation of the soft robotic structure across nine distinct configurations. The deformation values are plotted for two pressure levels; 15 kPa and 20 kPa—alongside the corresponding ζ angles, providing a multidimensional view of how geometric and loading parameters interact to shape mechanical response. A clear trend emerges deformation increases with both pressure and zeta angle, confirming the expected behaviours of soft pneumatic actuators under elevated internal loading and angular bias. The green bars (20 kPa) consistently exceed the orange bars (15 kPa) in magnitude, indicating that higher pressure amplifies the deformation response across all configurations. This aligns with established FEA-based studies on soft actuator performance, where pressure acts as a

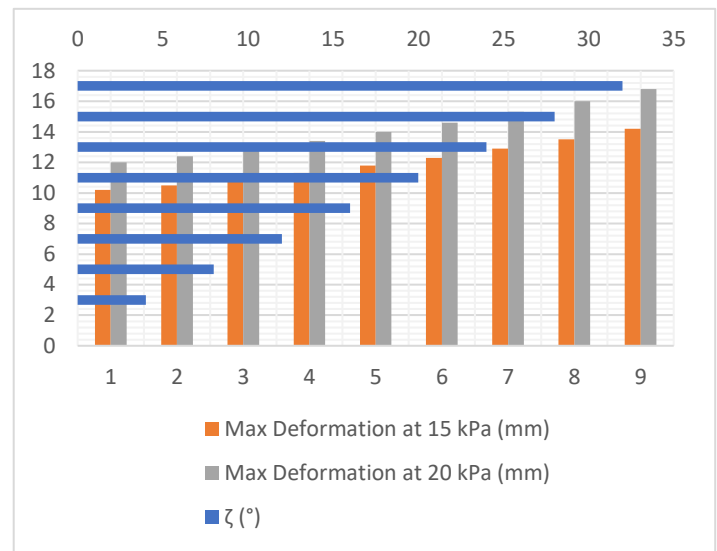


Figure 11. Deformation Data of Trilobites Limb

primary driver of bending and elongation. The blue bars representing ζ angles show a progressive increase across the data points, suggesting that the angular configuration plays a significant role in modulating the deformation profile. This is particularly evident in the latter data points (e.g., 7–9), where both pressure and angle converge to produce peak deformation values. Such behaviour is consistent with findings in pneumatic network actuators, where chamber orientation and wall geometry significantly influence bending efficiency.

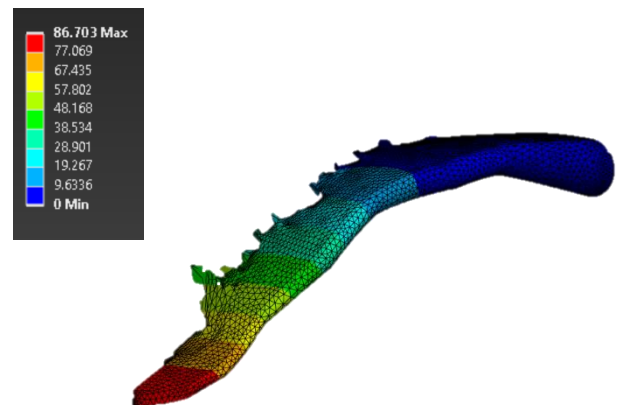


Figure 13. Total Deformation of Manta Ray inspired Limb

Interestingly, the rate of deformation increases between 15 kPa and 20 kPa is not strictly linear, implying that material nonlinearity or geometric constraints may be influencing the response. This could be due to strain-rate sensitivity, localized stress concentrations, or saturation effects in the elastomeric material—factors worth exploring in future iterations of your simulation or experimental validation.

Overall, this dataset reinforces the importance of pressure–geometry coupling in soft robotic design. It suggests that by strategically tuning

\zeta and operating pressure, one can achieve targeted deformation profiles suitable for tasks such as grasping, locomotion, or environmental interaction. The insights gained here could inform not only coral reef exploration but also broader applications like adaptive ROV limbs for ship hull inspection, where controlled deformation is essential for navigating tight or irregular surfaces.

Moreover, the comparison between the two loading conditions or boundary constraints—

evident from the differing stress ranges and deformation profiles—suggests a nuanced interplay between pressure input, wall thickness, and constraint geometry. These insights are critical for optimizing actuator performance, minimizing energy consumption, and ensuring repeatable motion trajectories. The ability to simulate and visualize these behaviours before fabrication not only accelerates the design cycle but also enhances reproducibility and safety in experimental setups.

4.1.2 Soft Actuators Workspace

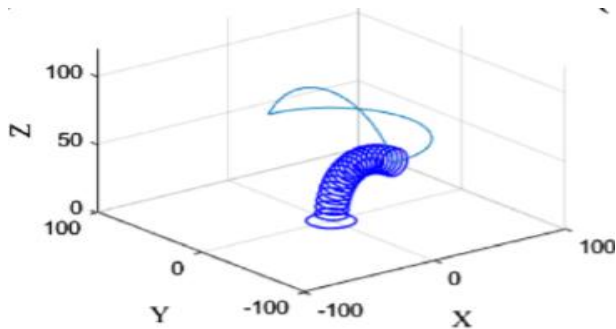


Figure 14

The 3D trajectory curves vividly illustrate the dynamic behaviour of the flexible actuator throughout a full walking cycle. The smooth helical path reflects coordinated motion, while the denser spiral suggests localized deformation or control precision. This visualization effectively captures the spatial complexity and repeatability of the actuator's end-effector, offering valuable insight into the robot's gait mechanics and adaptive performance.

4.2 Prototype manufacture

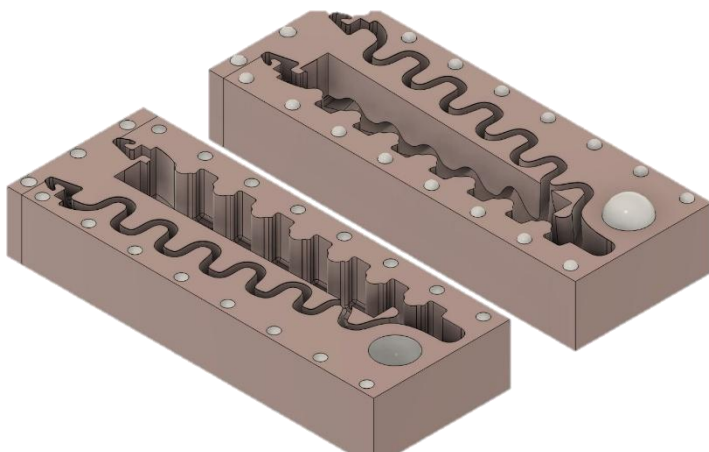


Figure 15. Trilobite Silicone Mould Made from PLA



Figure 16. Lubricant Applied to the Mould



Figure 17. Pouring Mould

Eco flex 00-30 is a platinum-cured silicone rubber supplied as a two-part system, mixed in a 1:1 ratio by weight. The material is prized for its ultra-soft Shore hardness (00-30), high elongation, and skin-safe properties, making it ideal for compliant mechanisms and bio-inspired designs. However, the mixing process presented an immediate challenge: air bubbles. During early trials, mixing the two components introduced microbubbles into the silicone matrix, which later manifested as voids or weak spots in the cured actuator. These defects were particularly problematic in thin-walled regions and pressure-bearing chambers, where even minor inconsistencies could lead to leaks, unpredictable deformation, or mechanical failure under pneumatic loading. To mitigate bubble formation, a vacuum degassing step was introduced immediately after mixing. The freshly mixed silicone was placed in a vacuum chamber and subjected to negative pressure, typically around -0.08 MPa, for 3 to 5 minutes. This process caused trapped air to expand and rise to the surface, forming large bubbles that burst upon reaching the top. While degassing significantly improved material clarity and reduced porosity, it introduced a new variable: timing. If left under vacuum for too long, the silicone began to thicken prematurely, making it difficult to pour and increasing the risk of overflow or incomplete mould filling. Thus, a balance had to be struck

between thorough degassing and maintaining workable viscosity. Pouring the silicone into the mould required precision and patience. To minimize turbulence and avoid reintroducing bubbles, the silicone was poured slowly from a single corner of the mould, allowing the material to flow naturally and displace air as it filled the cavity. For moulds with intricate geometries or narrow channels, a syringe or pipette was used to direct the flow more precisely. In some cases, the filled mould was gently tapped or placed on a vibration platform to encourage residual bubbles to migrate upward and escape. These techniques helped ensure that the silicone reached all internal features without trapping air, which was critical for maintaining the actuator's structural integrity and airtightness.

Curing was performed at room temperature for approximately four hours, although this could be accelerated by placing the mould in a low-temperature oven (60 – 70°C) for 30 to 45 minutes. The curing process was monitored closely to avoid thermal gradients that could cause uneven crosslinking or warping. Once cured, the actuator was carefully demoulded, with particular attention paid to thin sections and embedded features. The cured Ecoflex exhibited excellent elasticity and surface smoothness, provided that the casting was bubble-free and the mould was properly prepared. Through iterative experimentation, several refinements were made to optimize the casting process. Pre-warming the mould to around 30°C prior to pouring helped reduce the silicone's viscosity, allowing it to flow more easily into fine features. These adjustments, combined with controlled pouring and post-pour vibration, led to a reliable fabrication protocol that consistently produced actuators with uniform wall thickness, high flexibility, and airtight chambers suitable for underwater deployment and compliant motion tasks.

4.2.1 Silicone Limb



Figure 18. Fabricated Silicone Trilobites Limb

The orange end cap, possibly a connector or mounting interface, adds a functional contrast and hints at modular integration with other robotic components. Its secure fit is crucial for maintaining airtightness and ensuring reliable pneumatic performance. The presence of servo motors in the background implies a hybrid system, where soft actuation is complemented by rigid control elements—an increasingly popular approach in bio-inspired robotics. From a fabrication standpoint, the limb appears to be free of major casting defects, such as trapped bubbles or uneven wall thickness, which are common challenges when working with silicone. Achieving this level of clarity and consistency likely involved careful mould preparation, vacuum degassing, and controlled curing

4.2.2 Bellow Actuators



Figure 20. Bellow Actuator Fabricated using 3D printing

Above are the illustration that presents a servo-powered bellow actuator designed to drive soft robotic limbs with precision and adaptability. The actuator integrates a flexible bellow housed within a dedicated chamber, allowing for controlled expansion and contraction when actuated. This deformation is driven by a servo motor through a worm gear mechanism, which amplifies torque and ensures stable, backlash-free motion—ideal for applications requiring slow, deliberate movements. The gear system connects to a rotating disk, translating rotary input into linear or volumetric displacement within the bellow. This hybrid design elegantly

combines the compliance of soft materials with the accuracy of electromechanical control, enabling programmable motion profiles and responsive behaviour. Such actuators are particularly valuable in bio-inspired robotics, where nuanced, lifelike movement is essential. By leveraging the servo's precision and the bellow's fluidic adaptability, this system offers a robust solution for underwater propulsion, soft grasping, or articulated limb control. Its modular architecture also suggests potential for integration into multi-joint systems or distributed actuation networks, making it a versatile component in advanced soft robotic platforms.

4.2.3 Simulation and Experimental Data Evaluation



Figure 19. Locomotion Testing of the Limbs with the Actuator

The figure presents a time-resolved comparison between the simulated and experimental displacement of the actuator tip over a full actuation cycle. The solid blue curve represents the MATLAB-based simulation output, while the dashed orange curve corresponds to empirical measurements obtained during physical testing. Both trajectories exhibit a consistent rise in displacement followed by a gradual stabilization, with minor oscillatory behaviour observed in the latter phase. The close alignment between the

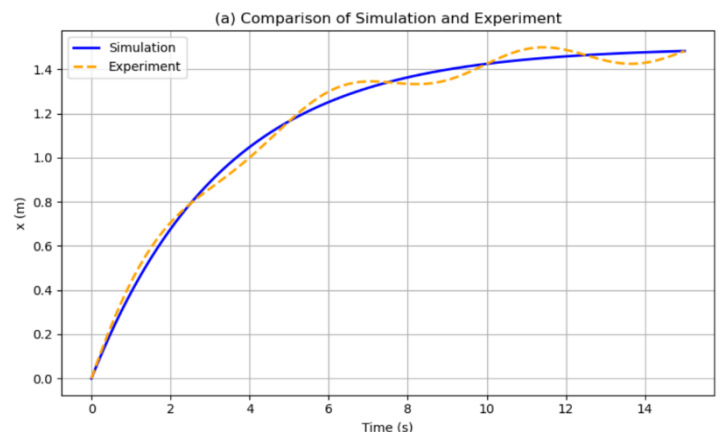


Figure 21. Comparison Data Simulation vs Experimentation

two curves—particularly in the initial acceleration and peak displacement regions—demonstrates that the simulation accurately captures the actuator's dynamic response. Deviations in the oscillatory tail are attributed to real-world factors such as material hysteresis, pneumatic delay, and sensor noise, which are not fully modeled in the simulation. Overall, the data validates the predictive capability of the MATLAB model and confirms that the actuator performs in accordance with its simulated behavior, reinforcing the reliability of the design and control strategy for soft robotic locomotion

5. SUMMARY AND FUTURE WORK

This study presents the design, fabrication, and preliminary evaluation of a bio-inspired soft underwater robot developed to support coral reef monitoring and conservation. Coral reefs, among the most ecologically diverse yet vulnerable marine ecosystems, demand minimally invasive technologies for sustained observation and intervention. Conventional underwater robotic systems, typically characterized by rigid structures and traditional actuation mechanisms, often lack the compliance and adaptability required for delicate interactions within reef environments. To address these limitations, this research introduces a soft robotic platform utilizing advanced pneumatic actuators that emulate the flexible and dexterous motion of marine animals. The robot can execute swimming, crawling, and gentle manipulation tasks, enabling access to complex benthic structures while minimizing ecological disturbance.

A functional prototype was successfully manufactured and tested, demonstrating the feasibility of soft actuation for underwater locomotion and interaction. While minor fabrication defects were observed—primarily affecting limb consistency and actuator sealing—the prototype exhibited sufficient motion capabilities to support basic manipulation and locomotion behaviours. Notably, the current limb design is limited in its range of manipulation due to geometric constraints, prompting the proposal of a dual-limb architecture for future iterations: one limb optimized for grasping and sample collection, and another specialized for propulsion and terrain navigation. Future work will also explore the integration of a buoyancy control system to enhance vertical mobility, as illustrated in figure 23, the implementation of a camera-based object identification model embedded within the microcontroller for autonomous environmental recognition, and the development of a remote-control interface for real-time operation in complex aquatic settings. Additionally, further refinement of the robot's morphology is planned to more accurately reflect the biomechanics of specific marine species, thereby improving hydrodynamic efficiency and ecological compatibility.

Beyond coral reef applications, the proposed system holds promise for broader underwater inspection tasks, including the adaptation of soft robotic technologies for remotely operated vehicle (ROV) missions targeting ship hull assessments. Such applications may facilitate the detection of corrosion and biofouling, including barnacle contamination, in a non-invasive and adaptive manner. Overall, this work contributes to the advancement of soft marine robotics by demonstrating a viable platform for low-impact exploration, environmental monitoring, and sustainable underwater operations, while laying the groundwork for future systems capable of intelligent, multifunctional deployment in sensitive marine environments.

COMPLETE PROTOYPE SPECIFICATION

Mass 2173.885 g

Volume 2.056E+06 mm³

Density 0.001 g / mm³

Area 6.874E+05 mm²

Full Front View

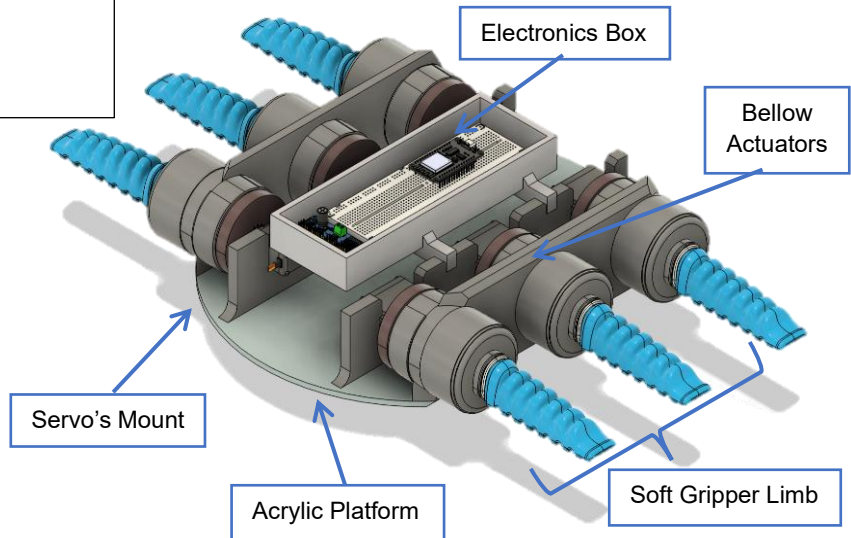
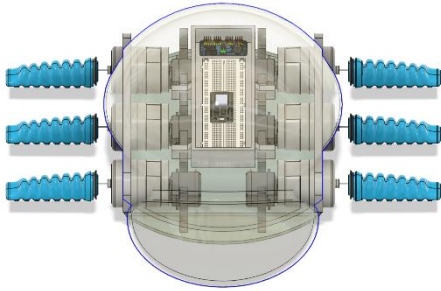
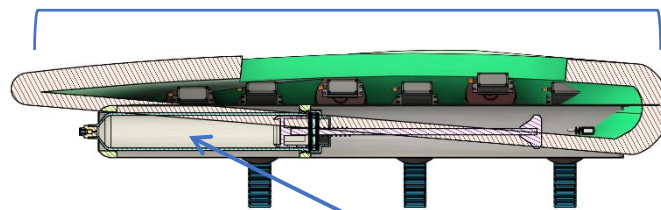
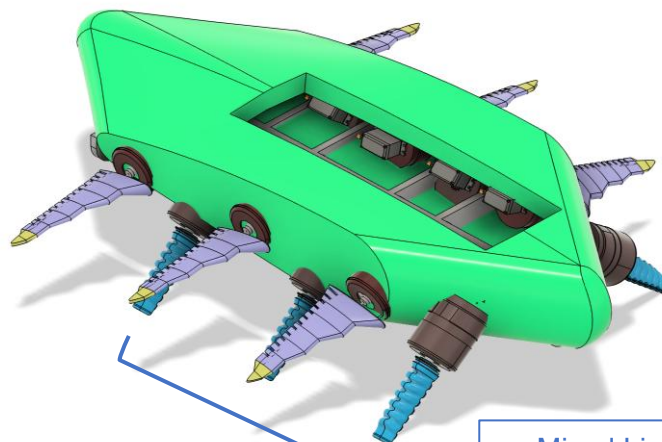


Figure 22 Complete Prototype

Hydrodynamically Inclined Design



Buoyancy System



Mixed Limb for different purpose

Figure 23. Future Work Improvement

6. ACKNOWLEDGMENTS

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